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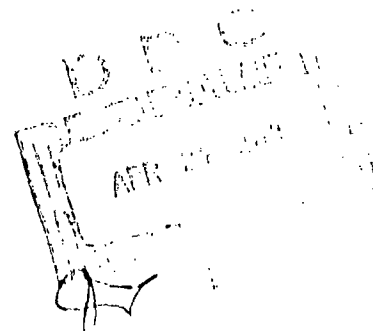
ETL-0117

**RADAR IMAGE SIMULATION: VALIDATION OF
THE POINT SCATTERING METHOD**

Volume One

J. C. Holtzman
V. H. Kaupp
J. L. Abbott
V. S. Frost
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September, 1977



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Prepared for:

U. S. ARMY ENGINEER TOPOGRAPHIC LABORATORIES
Fort Belvoir, Virginia 22060
CONTRACT DAAG53-76-C-0154



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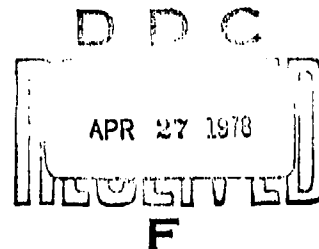
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VOLUME ONE

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(cont.) and other flight parameters. Second is a quantitative validation of a PPI model specialized to making reference scenes for a terminal guidance system (using the Correlatron*).¹

The results obtained have shown the simulated radar images to be accurate representations of the ground scenes at the microwave frequencies they modeled. The comparisons were shown to be very favorable. Preliminary results of the guidance test have been very satisfactory.

Data base construction techniques are also discussed. Alternate input intelligence data sources (high-resolution aerial photographs, maps, infra-red) for feature extraction are reviewed. A conceptual design for an interactive feature extraction system is discussed.

*Correlatron is the name of a two-dimensional cross-correlation measuring device manufactured by Goodyear Aerospace. The ETL has a Correlatron installed in a test configuration.

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RADAR IMAGE SIMULATION VALIDATION OF THE POINT SCATTERING MODEL Volume I

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ABSTRACT

The purpose of this report is to present the validation of the Point Scattering Radar Image Simulation Model and its software implementations developed at RSL (Remote Sensing Laboratory, University of Kansas, Lawrence, Kansas). The work was sponsored by ETL (Engineer Topographic Laboratories, U. S. Army, Fort Belvoir, Virginia). Two different instances of model validation are reported. First is validation of both SLAR (Side-Looking Airborne Radar) and PPI (Plan-Position indicator) radar simulation models by comparison of simulations to real images (of exactly the same ground swath) having the same look direction and other flight parameters. Second is a quantitative validation of a PPI model specialized to making reference scenes for a terminal guidance system (using the Correlatron^{*}).

The results obtained have shown the simulated radar images to be accurate representations of the ground scenes at the microwave frequencies they modeled. The comparisons were shown to be very favorable. Preliminary results of the guidance test have been very satisfactory.

Data base construction techniques are also discussed. Alternate input intelligence data sources (high-resolution aerial photographs, maps, infra-red) for feature extraction are reviewed. A conceptual design for an interactive feature extraction system is discussed.

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PREFACE

This document was prepared by the Kansas Simulation Group, Remote Sensing Laboratory (RSL), The University of Kansas, Lawrence, Kansas, to report the results of a Radar Simulation Study performed under Contract DAAG53-76-C-0154, dated 15 May 1976, with the Engineer Topographic Laboratories (ETL), Fort Belvoir, Virginia. This Radar Simulation Study was performed to validate the point scattering radar image simulation model which had been developed previously, to investigate terrain feature extraction techniques for constructing category data bases (digital ground model) for radar image simulation, and to use the point scattering radar image simulation model to generate radar reference scenes for terminal guidance applications.

The work and services to be provided under this contract were organized into two separate tasks. A summary of these tasks, collecting and grouping activities according to their relationships to these tasks, would be:

Task 1 - Simulation Systems Approach

The point scattering radar image simulation model will be used to generate simulations of a test site centered around the Pickwick Landing Dam located in Tennessee. The purpose of these simulations will be to validate the simulation technique which has been developed. The subtasks to be performed under this task are:

- (1) Perform a study to validate the point scattering radar image simulation model for Side-Looking Airborne Radar (SLAR) applications by making SLAR simulations of the Pickwick test site. The data base of Pickwick for the simulation (Subtask (3)) is to be made only from maps and optical imagery. After the SLAR simulation is complete, it will be compared to original furnished radar imagery and differences will be analyzed.

(2) Perform a study to validate the point scattering radar image simulation model for Plan-Position Indicator (PPI) radar applications by making PPI simulations of the Pickwick test site. The data base to use is the one constructed in Subtask (3), below. The PPI simulation model will be developed using a polar coordinate scan so that PPI radar simulations can be made in the correct geometry. After the PPI simulation is complete, it will be compared to the SLAR simulations produced in (1), above and differences will be analyzed. This approach is being used because real PPI imagery of the Pickwick site is not available.

(3) Construct data bases of the Pickwick Landing Dam test site for model validation. The appropriate planimetric terrain features will be extracted from optical photography and maps. Investigations will be conducted to develop automated terrain feature extraction techniques. The man hours for this feature extraction process will be recorded for comparing human photo interpretation methods for the same area when interactive data base construction techniques become available. Using digital elevation data and the planimetry extracted from photos only, a digital data base will be produced.

Task 2 - Advanced Simulation Methods

The point scattering radar image simulation model will be applied to generate reference scenes of a test site centered around the Pickwick Landing Dam located in Tennessee for testing by the Correlatron* for terminal guidance applications. The purpose

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of these reference scenes will be to evaluate the simulation technique for reference scene generation and to measure quantitatively the simulation results. The subtasks to be performed under this task are:

- (1) Produce PPI radar reference scenes appropriate for terminal guidance. The final product will be digital tapes of the reference scene simulations.
- (2) Construct data base of the Pickwick Landing Dam test site for terminal guidance studies. The appropriate planimetric terrain features will be extracted from optical photography and maps. The man hours for this feature extraction process will be recorded, comparing photo interpretation methods with interactive automated methods for the same area when such methods become available. Using digital elevation data and the planimetry extracted from photos only, a digital data base will be produced. Repeat the process using existing radar imagery, maps, and digital elevation tapes.

Obviously, the work and services to be performed under this contract were very extensive, spanning many disciplines, and drawing upon the knowledge and experience of geographers, electrical engineers, botanists, and computer scientists. To report these diverse activities in a coherent fashion is difficult. The format of this document has been designed to simplify, as much as possible, reporting this work.

The document is divided into two volumes to reduce the bulk that must be handled at any one time. Volume I reports the work and results with technical details deferred to the appendices. Volume II is a collection of appendices containing the individual technical details of the work reported in the first volume. In addition to reducing the bulk which must be handled, dividing the document into two volumes adds flexibility; it is easier to turn to the appropriate appendix in Volume II for technical details while keeping the work and results description open for reference in Volume I.

The organization of Volume I is structured around the basic work being reported. As can be seen in the summary of the work and services specified under this contract, there are listed two tasks and five subtasks. Upon inspection, it can be seen that the five subtasks are really only four different activities: (1) SLAR Validation; (2) PPI Validation; (3) Reference Scene Generation; (4) Data Base Construction/Feature Extraction Techniques. Volume I is organized according to these major activities. The format of Volume I and the relationships of each section to the appropriate subtask of the work and services is as follows:

<u>Document Section</u>	<u>Description of Work and Results</u>	<u>Statement of Work Task - Subtask</u>	
1	Introduction and summary of results	All	
2	SLAR Validation	1	1
3	PPI Validation	1	2
4	Terminal Guidance Applications	2	1
5	Data Base Construction/Feature Extraction Techniques	(1 2)	(3 2)

Volume II has a simple organizational plan. It is an alphabetical listing of the appendices required to support the work and results reported in Volume I. These appendices represent the technical information necessary to support the discussions of work and results in Volume I. There are fourteen appendices provided in Volume II as follows:

Appendix	Technical Report No.	Title	Date
A	TR 319-1	"Construction of a Geometric Data Base for Radar Image Simulation Studies"	July, 1976
B	TR 319-2	"Baseline of Planimetric Data Base Construction: Pickwick Site"	July, 1976
C	TR 319-3	"Digital Elevation Data Base Construction: Pickwick Site"	July, 1976
D	TR 319-4	"Digitization of Pickwick Site Data Base"	February, 1977
E	TR 319-21	"Increased Resolution of Planimetric Data Base: Pickwick Site"	March, 1977
F	TR 319-5	"Medium Resolution Digital Ground Truth Data Base"	August, 1977

G	TR 319-7	"Backscatter Data for the Digital Radar Image Simulation of the Pickwick, Alabama Site"	February, 1977
H	TR 319-9	"Medium Resolution Radar Image Simulation of Deciduous Forests: A Study of Candidate Techniques"	August, 1977
I	TR 319-8	"Digital Model for Radar Image Simulation and Results"	August, 1976
J	TR 319-19	"Digital PPI Model for Radar Image Simulation and Results"	August, 1977
K	TR 319-15	"Investigation of an Interactive Approach for Radar Image Simulation"	March, 1977
L	TR 319-24	"Automated Techniques in Feature Extraction"	June, 1977
M	TR 319-25	"Interactive Feature Extraction System Framework"	June, 1977
N	TR 319-26	"Image Handling and Processing"	June, 1977

PURPOSE

The purpose of this document is to report the results of a Radar Simulation Study conducted by the RSL (Remote Sensing Laboratory, University of Kansas) under contract with ETL (Engineer Topographic Laboratories, United States Army, Fort Belvoir, Virginia). The Radar Simulation Study was performed to test the Point Scattering Radar Image Simulation Model developed and reported in previous work^{1,2}. The Point Scattering Model was applied to three specific problems in this study, and the work performed and results obtained are reported in this document. The three specific applications tested in this study are: (1) SLAR (Side-Looking Airborne Radar) Model Validation; (2) PPI (Plan-Position Indicator) Radar Model Validation; (3) Terminal Guidance Applications. In addition to the implementation and testing of these three applications of the simulation model, much effort was expended in peripheral activities required to support the main efforts. Principal of these was data base construction with emphasis on feature extraction methods and techniques. As these activities are of critical importance to successful implementation of radar simulation models and to successful utilization of these models, the purpose of this document is extended to report these support activities, also.

¹ Holtzman, J. C., V. H. Kaupp, R. L. Martin, E. E. Komp, and V. S. Frost, "Radar Image Simulation Project: Development of a General Simulation Model and Interactive Simulation Model, and Sample Results," TR 234-13, Remote Sensing Laboratory, The University of Kansas, February, 1976.

² Holtzman, J. C., V. H. Kaupp, and J. L. Abbott, "Radar Image Simulation Project," TR 234-15, Remote Sensing Laboratory, The University of Kansas, September, 1976.

SCOPE

The scope of the work performed in this Radar Simulation Study was limited to testing the Point Scattering Radar Image Simulation Model against one specific area. The three applications (SLAR, PPI, and Terminal Guidance) of the simulation model were each tested against this one area. The area selected for this test of the simulation model was the topographic region in the states of Tennessee, Alabama, and Mississippi, centered on the northwest corner of the powerhouse at the Pickwick Landing Dam, Tennessee. The SLAR and PPI validation work was limited to forming a sequence of radar image simulations from two different look directions of selected subregions of the Pickwick test site and comparing these simulated radar images to real images (of the same regions) having the same look directions. The terminal guidance work was limited to producing reference scenes of the Pickwick site from one altitude for running on the Correlatron.* The data base construction/feature extraction work was limited to preparation of two data bases of the Pickwick site: (1) Data base for SLAR and PPI validation work, (2) Data base for Terminal Guidance work.

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EXECUTIVE SUMMARY

The Point Scattering Model (PSM) for radar simulation developed at RSL (Remote Sensing Laboratory, University of Kansas, Lawrence, Kansas) has been applied to three different problems for testing and validating. The results of applying PSM to these three problems and testing the applications are reported in this document. This document begins with an overview of radar simulation where the problem of simulation is discussed. In the Introduction section (1.0) the work performed (1.2) and the results obtained (1.3) are summarized and, in addition, some significant qualifications, limitations, and constraints of the model (1.4) are discussed. In the next three (3) sections the simulation work performed for each of the three (3) different simulation problems is reported; SLAR simulation and validation (section 2.0), PPI simulation and validation (section 3.0), and reference scene simulation (section 4.0). The PSM is a digital approach to radar simulation. A prime requisite of the PSM is a digital symbolic model of the ground (ground truth data base) of the target area for which radar simulations are desired. The work performed in constructing the ground truth data bases used for the simulation tasks reported in this document is described in Section (5.0). Section 6.0 contains the conclusions reached in the course of performing this work and section 7.0 contains a number of recommendations, both long range and short range goals, which are a natural outgrowth of this work.

The radar simulation work and validations performed fall into two different classes. The first class is qualitative and the second is quantitative. The SLAR and PPI simulation and validation work (sections 2.0 and 3.0) is qualitative. The results produced for this class show the geometric fidelity, textural consistency, and relative graytone accuracy of simulated images to be excellent by comparison to real images of the same scenes. These comparisons were performed for simulations representing two different look directions of areas representing approximately 36 square miles, each. The implications of these qualitative

results are that not only are the PSM and its software implementation verified, but also the ground truth data bases and associated elevation data, feature categorizations, and microwave reflectivity data are verified. The reference scene simulation work (section 4.0) is quantitative and, thus, belongs to the second class. Five reference scenes were produced in support of a terminal guidance test employing the Correlatron, an area cross-correlation guidance device. The complete results are not yet available; however, preliminary indications are that the reference scenes produced met or surpassed requirements. Since this test involved using the Correlatron to measure the quality of reference scenes as compared to actual radar data of the same sites, it represents a quantitative measure. Not only do the simulations look good when compared to real images of the same site, but also they are faithful enough to the true characteristics of a radar image of a given scene that an electronic "black box", the Correlatron, can use them to derive accurate guidance information.

Two different ground truth data bases were constructed to evaluate alternate kinds of source intelligence data from which to make data bases in support of simulation. One data base was constructed using high-resolution aerial photographs and maps as the source intelligence data for feature extraction. The other was built using maps and aerial photographs for the geometry of a scene and radar imagery for feature extraction. Construction time was recorded for both data bases. It was found that construction time did not vary appreciably as a consequence of using the two different intelligence data sources.

As a natural consequence of building ground truth data bases for simulations, feature extraction techniques were evaluated and it was conjectured that construction time and, perhaps, final data base quality can be improved by the use of suitable interactive feature extraction techniques. A simplistic interactive feature extraction concept was reported.

In conclusion, the results produced under this contract clearly verify the validity of the PSM for radar image simulation, its software

Implementations, the ground truth data bases produced and feature extraction techniques used, and the microwave reflectivity data (empirical σ^0) used. They also demonstrate the versatility and utility of the PSM by, in particular, the spectacular results from applying PSM to a "real-world" application, terminal guidance. The work performed and results produced clearly suggest that radar image simulation has become a viable tool and is ready for application to many different present and future applications.

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COMPUTER PROGRAMS

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RADAR IMAGE SIMULATION: AN OVERVIEW

It is the purpose of this section to try to describe radar image simulation and to define terms and concepts, and to try to place into a proper perspective all the various individual parts. This is being attempted in the hope that by explaining radar simulation in such a manner, the work performed and results obtained in the Radar Simulation Study reported in this document will have greater meaning to the casual reader. More importantly, we hope to provide in sufficient depth an understanding of the process so that greater appreciation for radar simulation, its needs, problems, and complexities, will be developed. Much work has been done previously and many milestones have been achieved. But unless one is intimately familiar with the problems, the investigations, and solutions, he will not realize what has been accomplished. Neither will he realize what is left to be done. Further, without this basic understanding of radar simulation, it is very difficult to accept radar simulation for the tool that it is and to visualize how radar simulation can be applied to solve present and future problems. With the advent of the Point Scattering Radar Image Simulation Model, developed at the Remote Sensing Laboratory (RSL), University of Kansas, Lawrence, Kansas, radar simulation has become an engineering tool, a tool to be used. Previously, radar simulation had been somewhat akin to black magic: Whatever worked is what was done. Our simulation model is mathematically rigorous and exactly predictable. Here, we want to explain, in words, not equations, necessarily, the development of the model, and we want to define terms as we come to them; terms such as data base and backscatter. The level of discussion is purposely aimed for readers who are not intimately familiar with radar systems and the simulation of radar systems. No attempt is made in this discussion for mathematical rigor. Tutorial explanations have been the rule, rather than the exception. In developing this section we have tried very hard to say things in such a way that they could not be misconstrued (one is never completely successful in this) and we tried to prevent unintentional errors, either of omission or commission.

1. Radar Systems

The starting point for this explanation of radar simulation is the radar system being simulated. Before we can discuss modeling and simulation of radar, we must first define what is being modeled and simulated. Figure I presents an illustration of the basic components of an imaging radar system. The bare essentials are shown. Note that three separate pieces are shown: (1) Radar; (2) Ground; (3) Image. Each piece by itself represents only a single item. Together they comprise a radar system. The radar system, for simulation purposes, is defined to be the closed system of radar, ground, and image. It is this complete system which is being modeled and this model which produces the simulations.

Very briefly, modern imaging radars work in the following way. The transmitter produces a pulse of electromagnetic energy which propagates at the speed of light to the ground, confined by a directional antenna to illuminate only a narrow swath on the ground. The pulse of energy strikes the ground and interacts with it. A small fraction of the power incident on the ground is re-radiated from the ground back to the radar and is received by the antenna. This received power is detected by the receiver. Refer to Figure II. Imagine that the radar system shown in Figure I carried by either an aircraft or a spacecraft, is located at the position labeled A in Figure II. For present purposes, let's assume that the imaging radar we are discussing is a SLAR (Side-Looking Airborne Radar); the principles hold for any other radar (e.g., PPI), but the geometry may be different.

If the vehicle carrying the SLAR is traveling in the direction of the arrow and if the SLAR is sensing the ground out to the right side of the vehicle, then the geometry is shown in Figure II. Assume the radar, located at the point A, transmits a single pulse. This pulse of energy spreads out in all directions within the constraints imposed by the directional properties of the antenna. Assume the antenna allows the pulse to spread in the direction labeled range but limits the spread of the pulse to a very small distance in the direction labeled azimuth. Then, for this pulse, a narrow strip in azimuth extending from beneath the

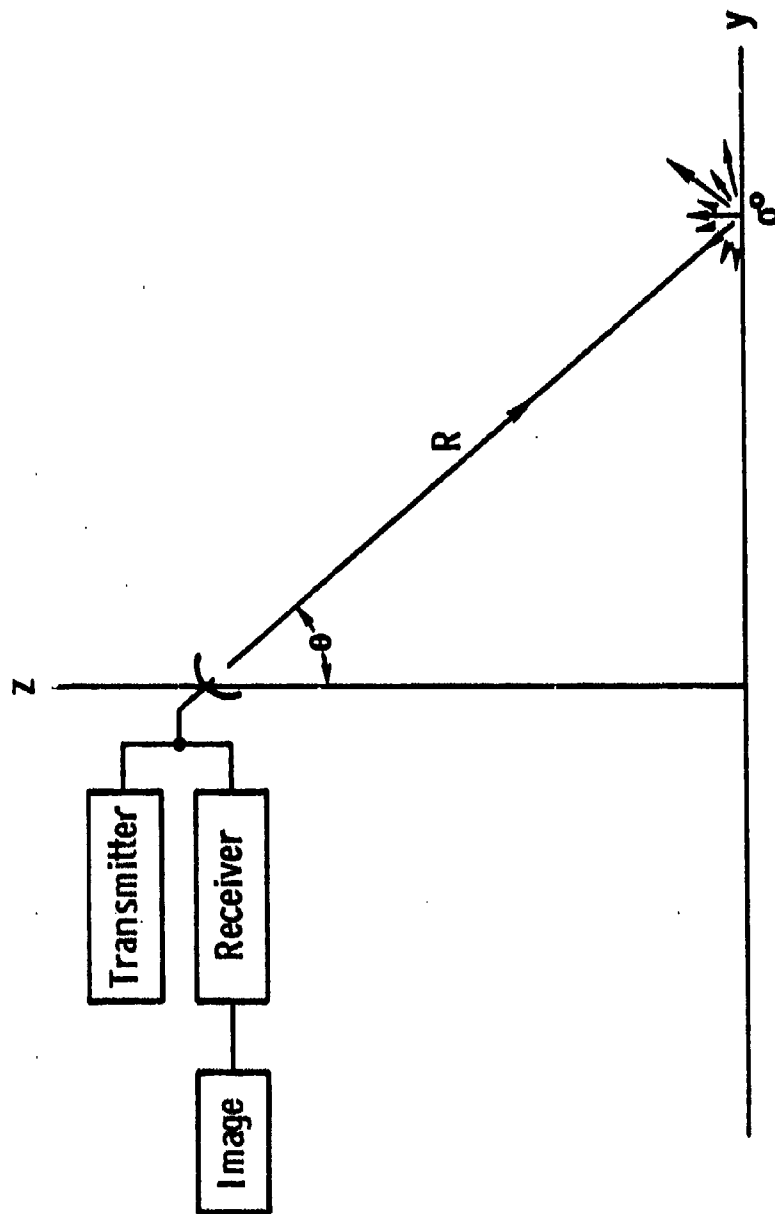


Figure 1. Fundamental Block Diagram - Radar System

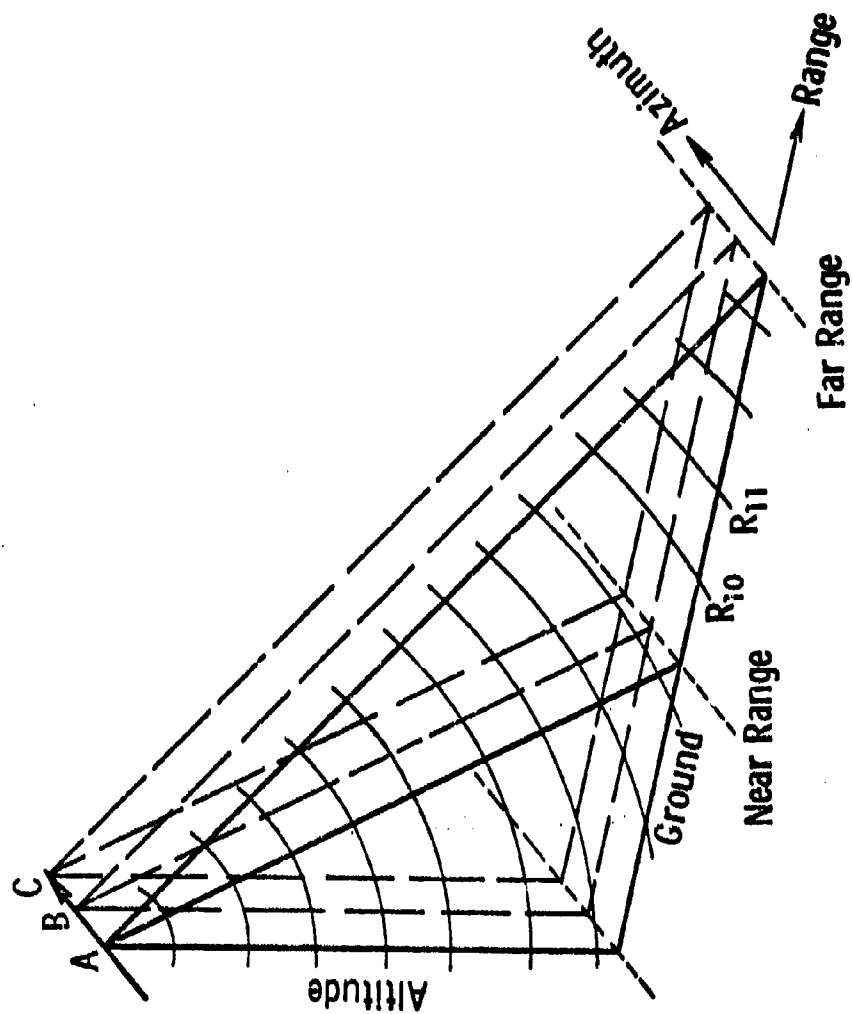


Figure II. Conceptual Model of SLAR

radar all the way out in range will be illuminated. The concentric arcs, centered on the radar, shown in Figure II, represent successively later times as a single pulse radiates in space. The point where the arc labeled R_{10} intersects the ground will be illuminated by this pulse before the point illuminated by R_{11} . The reradiated power from R_{10} will be received by the radar before the power from R_{11} . Since this is the case, the receiver will detect the signal from R_{10} before R_{11} .

The output of the receiver is a video signal corresponding to the relative intensities of the power received from all the points illuminated on the ground, and ordered in time by the relative distance of each point to the receiver (the intensity of R_{10} will be detected and output before R_{11}). This video signal is used to produce the image (conceptually shown as a block in Figure I). As the power from all the points on the ground is returned and detected, the variations in intensity caused by the scattering properties of the different features in the scene can be used to intensity modulate the electron beam of a CRT (Cathode Ray Tube) which is subsequently photographed. Many ways exist to record the image; this is one. If the electron beam starts to sweep the face of the CRT at the time corresponding to the roundtrip distance to the point labeled near range and continues the sweep to the time corresponding to the roundtrip distance to the point labeled far range, then the intensity variations modulating the electron beam during this interval will cause variations of light to appear across the face of the CRT. These variations of light on the face of the CRT are the scene response at the radar operating frequency and, thus, represent the image of that narrow strip illuminated by one pulse.

Now, while all of the previous processing is going on, the vehicle was moving. After all the desired energy from the first pulse has been processed, another pulse can be processed. Let the vehicle be located at the point B when the second pulse is transmitted. The energy from the second pulse is processed just like the first; all previous comments apply. The film is moved a little bit and the image of the second narrow strip is recorded on film. The vehicle moves to C, a third pulse is transmitted,

the film is moved a little, and the image of the third strip is recorded on film. And, so on, until the desired strip length has been imaged.

In capsule form, this discussion summarizes the operation of imaging radars. This is the system being modeled when we form simulated radar images. Now we would like to go one step further and show (by verbal arguments) in a little bit more detail the relationships and interrelationships between radar, ground, and image. Hopefully, we will explain such parameters as σ^0 in such a way that both a simple mental picture is presented of what it does and the complexities and problems associated with obtaining and using it are clarified. The vehicle itself is unimportant to radar simulation. The parameters associated with the flight, however, are of critical importance and they must be properly accounted for in the simulation model. The more important flight parameters are: (1) Altitude; (2) Heading; (3) Flight path location; (4) Speed. Variations of these parameters with time are especially important. These parameters define which ground spot is being imaged, the altitude, look-direction, and angle-of-incidence at which the radar views each point in the image, and the separation between successive points on the ground. "Look-direction" is a very important concept to imaging radars. It means, given a particular radar image of a portion of the earth, the direction, relative to the image, in which the radar was pointed. In Figure 1, the look-direction is from left to right: From the radar to the scene. Look-direction is important because radar images of scenes having some features higher than others (as is true of most terrain) will look very different depending upon the direction from which the radar viewed it. This very real property of radars must be included in the simulation model. "Angle-of-incidence" is another very important concept to imaging radars. Among other things, the angle-of-incidence from the radar to each point in the image defines the brightness of each point relative to every other point; it is an important parameter. In Figure 1, the angle-of-incidence is shown as θ , the angle between a vertical line drawn from the antenna to the ground (perpendicular to the ground) and a line drawn from the antenna to the point on the ground being sensed. Again, this important property of the ground must be included in the simulation model.

The next aspect of an imaging radar system to be discussed is the mechanism by which the radar "views" the ground. The starting place for this discussion is the transmitter, shown in Figure I. The transmitter produces a short burst of electromagnetic energy (a pulse) which propagates at the speed of light confined by a directional antenna to illuminate a narrow swath on the ground. Assume the average transmitted power of this pulse to be P_T watts. If the pulse were allowed to radiate equally in all directions (isotropically) into free space, the power at a point a distance R from the radar would be reduced by the spreading of this pulse in all directions by a factor of $\frac{1}{4\pi R^2}$. The power density (power per unit area) at a point a distance R from the radar would then be given by $\frac{P_T}{4\pi R^2}$. But, the pulse is not allowed to radiate equally in all directions into free space. Instead, the pulse is confined by a directional antenna to illuminate a narrow swath on the ground. The antenna has directivity. This can be described by an antenna gain, G_T . Consider what the antenna does. It confines the transmitter power to radiate in a specific direction, instead of allowing it to radiate in all directions. If we pretend that we transmit higher power, throw away the antenna and allow this pulse to radiate isotropically (in all directions), and have chosen the transmitter power to give us the same power at the desired point on the ground as if we still had the antenna, then we can still use the expression just developed for the power density at a point a distance R from the antenna. The only thing we have to do to fix-up this expression is put in the new transmitter power. The new transmitted power is just G_T times larger than the previous case because that is what the antenna does. It makes the power density at a point appear as if it were produced by a transmitter having G_T times the power output, G_T being the gain of the antenna. Thus, the power density at a point on the ground a distance R from the radar would be described by $\frac{P_T G_T}{4\pi R^2}$.

Refer back to Figure I. We have just described the mechanism by which the radar illuminates the ground and have argued, qualitatively, what fraction of the transmitted power would reach each point on the ground. Look at the point in the figure at which the transmitted

energy strikes the ground. Arrows are pointing in all directions to show that, after striking the ground, this power is scattered in all directions. A very small fraction of this power is reradiated from each point in a direction back to the radar. The fraction of power reradiated back (backscattered) to the radar from each point is defined by σ , the effective backscatter area. The fraction of power reradiated back to the radar (σ) is an extremely complex parameter. It is easy enough to write the fraction of reradiation symbolically. We have already done that when we called it σ . To find the actual number for a fixed set of conditions is another matter, for σ varies with almost everything. This is an overdramatization, but it is intended to dispell the idea that getting σ was trivial, a notion that may have been engendered by our simplistic development. One simplification can be made immediately, if we normalize the backscatter to be independent of the ground spot size. To do this we simply write $\sigma^\circ A = \sigma$. The parameter σ° is called the differential scattering cross-section, a name meaning it is the backscatter per unit area. The area is specified by the symbol A and represents the area of illumination. The parameter (σ°) is normally used for radar return from the ground. As can be seen, it is a little easier to specify backscatter now because we have normalized area dependence out of the specification.

It is still exceptionally difficult to specify σ° , for it depends upon an amazing list of variables. This list of variables contains a combination of both radar and ground parameters. Included in this list of variables would be the following: (1) Radar parameter - Wavelength, polarization, direction of illumination; (2) Ground parameters (nature of the category) - Complex permittivity, roughness of surface, homogeneity of surface. This tidy little list means that the fraction of power reradiated back to the radar from each point on the ground varies with transmitting frequency (wavelength), polarization, look direction, and angle of incidence of the radar. If you change radars, or flight parameters, or both, the power returned to the radar from each point on the ground will be different - the image will look different. However, the ground parameters yield the greatest influence on radar images, for the power returned to the radar from each point on the ground changes as conditions at that point change.

Change the moisture content (drought, rain, hail, sleet, snow, ice, irrigation, etc.), or the backscatter category (trees versus marshes, different crops, new versus mature plants, agriculture versus bare ground - summer versus winter, leaves on trees versus no leaves on trees, new leaves versus old leaves, etc.) or the surface roughness (plow the ground, etc.), or the homogeneity (mix agriculture types, soil plus flora, mix trees and crops, mix soil types, etc.), and the power returned to the radar from each point on the ground changes; the image will look different.

Recall that what we are trying to do is to specify the fraction of power reradiated from a point on the ground back to the radar. For real radar systems, this is no problem for the answer to be automatic: illuminate the ground and a fraction of the power is reradiated back to the radar. It's only when we want to simulate the radar response to a given scene or to interpret the radar response to a given scene that we are faced with the problem of specifying the fraction of reradiation. There are two basic approaches to this problem. The first is to use a calibrated radar (called a scatterometer) to measure the backscatter of as many categories for as many variables as is desired. Then, catalogue these empirical backscatter data (σ^0) in a data bank versus the variables. For instance, catalogue them versus category (backscatter types), frequency (wavelength), polarization, angle of incidence, soil moisture, season (plant maturity), etc. Then, when simulating the radar image of a specific ground scene or interpreting a specific image, use the empirical σ^0 data (these data were probably collected from targets other than the one being simulated), as appropriate. Much work has been done to catalogue σ^0 data but much more remains. As an aside, all the simulated radar images presented in this document were made from empirical σ^0 data. It isn't very reasonable to expect to measure and catalogue σ^0 data for every backscatter category for every combination of the variables. This is where the second basic approach to the problem of specifying σ^0 comes in. The second approach is to use theoretical scattering models for σ^0 , as appropriate. Two different kinds of theoretical models can be used. The first model is one which predicts σ^0 for a given scattering category. The second model is one which will extrapolate empirical

(measured) σ^0 data across conditions (i.e., across frequencies). Even though the problem of specifying σ^0 is terribly difficult, the results presented in this document attest to the fact that much progress has been made.

To continue our discussion of how a real radar system operates, let's assume that we can find σ^0 data from either the literature or our data bank for the categories in a scene. As previously stated, before we took time out to discuss σ^0 , we were trying to specify the fraction of power reradiated from a point on the ground back to the radar. We decided to use the normalized backscatter per unit area (σ^0) to specify this fraction. Thus, at a point just above the surface in the direction of the radar, the power will be given by $\frac{P_T G_T \sigma^0 A}{4\pi R^2}$. This represents the power sent back from the scatterers on the ground.

Now, look again at Figure I. Note that the radar is a distance R from the ground. For the moment, let's forget σ^0 and pretend power being reradiated back radiates equally in all directions. Let's consider the point on the ground to be a transmitter producing a power given by $\frac{P_T G_T}{4\pi R^2}$ with this power radiating equally in all directions. Recall that due to spreading of power equally in all directions, the power at the antenna, a distance R from the ground, would be reduced by $\frac{1}{4\pi R^2}$. Recall also our discussion about a directional antenna. We can represent the ground as a directional antenna with weighted gain $\sigma^0 A$. Backscatter is a very directional parameter and in our analogy, describes the directional properties of reradiation from the ground and can be thought of as an antenna pattern weighting our otherwise isotropic radiation from the ground. Putting this together then, we find that the power density at the radar antenna is given by $\frac{P_T G_T}{4\pi R^2} \left(\frac{\sigma^0 A}{4\pi R^2} \right) = \frac{P_T G_T \sigma^0 A}{(4\pi R^2)^2}$ since the ground is assumed to have an antenna pattern given by $\sigma^0 A$.

The power received by the receiving antenna is the product of the power density (power per unit area) incident on the antenna with the effective receiving area (A_R) of the antenna. The effective receiving area of the antenna can be rewritten as $A_R = \frac{\lambda^2 G_A}{4\pi}$. The parameter λ

is the original transmitting wavelength and G_A is the gain of the receiving antenna. In the system we are discussing, the transmitting antenna is also used for receiving, thus $G_A = G_T = G$. This being the case, the average power received (\bar{P}_R) by the radar is specified by

$$\bar{P}_R = \frac{P_T G^2 \lambda^2 \sigma^0 A}{(4\pi)^3 R^4} \quad (1)$$

which is the famous radar equation.

Refer back to Figure 1. Up to this point, we have watched as the radar transmitted a pulse of energy to the ground. We observed the interaction of this pulse with the ground. We followed as the ground reradiated a fraction of this pulse back to the radar. And, we measured the power received by the radar at the antenna terminals. Now we need to process this power and form an image. From the antenna terminals, the received power is input to the receiver. The receiver amplifies, filters, and detects the useful signal from this input power. Receivers are designed to meet certain minimum fidelity requirements. Techniques are selected to optimize reproduction of the signal containing the terrain backscatter characteristics. For modeling purposes, let's specify the transfer function of the receiver symbolically as M . The symbol M represents the receiver transfer function, no matter how complex it may be. Thus, the intensity (I), or, in other words, the video output, of the receiver is given by the receiver transfer function (M) operating on the power input to the receiver (\bar{P}_R), which symbolically becomes $I = M\bar{P}_R$ where \bar{P}_R is given by equation (1).

For the purposes of discussing and modeling a radar system, specifying the receiver transfer function by the symbol, M , is quite legitimate. However, a word of caution is due. Receivers, in general, are very complex electronic devices which simply do not have perfect operating characteristics. When it becomes necessary, actually, to obtain the transfer function of a specific receiver (of a specific radar), it will be found that a typical receiver consists of a local oscillator, mixer, preamplifier, post-amplifier, detector, and video amplifier, all of

which must be modeled. The combined effect of these components on the terrain backscatter signal may be non-linear. Some typical non-linearities encountered in radar receivers include AGC (Automatic Gain Control), saturation of both the amplifiers and detectors, and low signal level non-linearities in detectors. All of these components and their effects must be accounted for properly when modeling a specific radar. This task must be performed when simulating radars. For now, we'll assume that task has been accomplished with the result specified as M.

There remains one final part of the radar system to discuss: The image. We have just defined the video (I) output of the receiver. Now, we want to convert this video signal into an image. Many ways are available. We select photographic film as the image medium for this discussion because that is the medium used when we simulate radar images. Unexposed photographic film generally consists of a transparency base coated with an emulsion of tiny silver halide grains. When exposed to the video output of the radar receiver, these silver halide grains undergo a complex change. Those grains that have absorbed enough energy change to metallic silver during development. The grains that did not absorb enough energy do not change to metallic silver during development and are washed off. The opacity, or photographic density (D), of the developed film will be directly related to the density of silver grains across the transparency. The density³ of the resultant image depends not only on the intensity (I) incident upon the film during exposure, but also on the transfer function of the film (γ is used to signify the transfer function of film in the linear portion of its dynamic range) and the photographic process used to develop the film. This relationship can be expressed in symbols as $D = \gamma \log_{10} I + \log_{10} k$ where k is a constant which depends upon the exposure time, and the film processing and development.

Refer back to Figure 1. We started with a pulse of transmitted energy, followed its propagation to the ground, defined the interaction of that pulse with the ground, followed the reradiation of a small

³ Goodman, J. W., "Introduction to Fourier Optics," McGraw-Hill, Inc. 1968.

fraction of that pulse back to the radar, and measured the power received at the antenna terminals. Then we discussed the transfer function of the receiver and found the intensity output of the receiver was related to the power input by $I = M\bar{P}_R$. Finally, we reviewed a few general properties of film and discovered that the photographic density of the developed film was given by $D = \gamma \log_{10} I + \log_{10} k$. Now, if we put all the pieces together by appropriate substitution for various parameters, we find that the image photographic density is related to intensity incident during exposure by $D = \gamma \log_{10} (M\bar{P}_R) + \log_{10} k$ where we substituted for I . Again, we can substitute Equation (1) for \bar{P}_R obtaining the final desired relationship

$$D = \gamma \log_{10} \left[\frac{MP_T G_T^2 \sigma^0 A \lambda^2}{(4\pi)^3 R^4} \right] + \log_{10} k$$

or (II)

$$D = \gamma \log_{10} \left[\frac{P_T G_T^2 \sigma^0 A \lambda^2}{(4\pi)^3 R^4} \right] + \gamma \log_{10} M + \log_{10} k$$

Equation (II) represents the final model for the radar system we have been discussing. The relationships between the power transmitted (P_T), ground interaction (σ^0), receiver transfer function (M), film transfer function (γ), and film exposure and development (k), are all explicitly stated. This model, Equation (II), represents the starting point from which the Point Scattering Radar Image Simulation Model is built.

II. Refinement of the Radar Model for Simulation: The Greytone Equation

In the previous section we discussed some of the basic principles of imaging radar systems. We developed a model for an imaging radar system, Equation (II). As it is written, Equation (II) accurately models the operational configuration of a radar system, but much more is needed to simulate an imaging radar system. Implicit in this equation, but not explicitly shown, are all the normal radar effects such as layover, shadow, range compression, etc. In the flight hardware radar system, these effects are automatically accounted for by the fact that the system detects and records the power returned from points on the ground according to how far away each point is, and Equation (II) properly models this. When we want to simulate imaging radars, however, we must incorporate specific provisions in the model for each of these, and other, effects.

The first order of business is to refine the basic radar system model, Equation (II), for implementation on a digital computer. That is, we need to build into the model convenient methods to increase our control over the input/output functioning of the model. There are three refinements which we can make to give us the added control. First, because we are using a digital computer, we can select the number of shades of grey (greytones) we want between black and white of which the image is to be made; this is accomplished easily by selection of the computer word length for each pixel (picture element in the image). Next, we can specify the radar dynamic range which is to be mapped into the optical dynamic range available in the final image. Finally, we can calibrate the scene so that a desired point in the image (representing a particular backscatter category at a specific altitude, range, and angle of incidence) has a defined greytone (shade of grey). When this refinement is completed, we will have converted Equation (II) into what is popularly called the Greytone Equation. These refinements are discussed in this section and the Greytone Equation is reported as Equation (IV).

The second order of business is to develop, using the Greytone Equation, what we call the Point Scattering Radar Image Simulation Model. The Point Scattering Radar Image Simulation Model is the name we give to the radar image

simulation computer programs which include software realizations of the Greytone Equation, layover, shadow, range compression, angle of incidence, local angle of incidence, etc. The Greytone Equation operates on the output of all of these interim products to produce the value of grey assigned to each pixel in a simulated radar image. The complete package, not just the greytone equation, is called the Point Scattering Radar Image Simulation Model. We will not discuss either the software implementation of the greytone equation or of layover, shadow, etc., and hence, we will not discuss the computer programs which incorporate all of these effects. This is beyond the scope of this section. Details of the development of these programs can be found in Sections (2), (3), and (4), and in the Appendices.

We will however, discuss the refinements of Equation (II) which lead to the Greytone Equation as this discussion will help interpret Equation (IV), the Greytone Equation. Since we are using a digital computer for implementation of the point scattering radar simulation model, the output, a simulated radar image, will be a digital matrix; one point in the matrix for each pixel in the image. Each point in the matrix is a computer word consisting of N bits. Each computer word in the output matrix represents a pixel and each pixel, therefore, consists of N bits. The computer is a binary machine, meaning that a word having N bits has 2^N different states. This means, then, each pixel in the image can take on any one of 2^N different states; the exact state selected depends, of course, on the data processed. Or, since in an image different states are different greytones (shades of grey), this means that the image is made up of 2^N different greytones. Thus, any image can contain as many greytones as is desired; merely select the appropriate N (e.g., $N=8$ means 256 different greytones). If the output image is being formed exclusively for use by humans, there is a debate over exactly how many greytones to use in an image. The general consensus seems to be that at least 64 shades ($N = 6$) but not more than 128 ($N = 7$) need to be used. This, of course, presupposes that the radar and image recording medium are capable of producing at least that many distinct shades of grey, and that the intended image use requires that many shades.

Now, let us determine how much of the simulated radar signal dynamic range is to be recorded in the available dynamic range of the photograph of

that simulated radar image by defining what signifies black and white in the output simulated radar image of our program. If we illuminate a developed image transparency, we can observe that in the light areas of the image (low photographic density, D) the illuminating light, incident intensity (I_0), is passed almost unimpeded, whereas, in the dark areas (high density) very little light, transmitted intensity (I_T), is passed. This observation can be used to our benefit since it can be expressed mathematically. The photographic density (D) is equal to the logarithm of the ratio of the incident to transmitted intensity. In symbols, this is $D = \log_{10}(I_0/I_T)$. Note that the relationship holds regardless of whether the transparency is a negative or a positive copy of the original. Now, specify values for black and white in the film transparency. By doing this we are effectively setting the simulated radar gain by defining the dynamic range of the radar signal we want to be in the simulated radar image. For a specific example let black be the case when the intensity transmitted (I_T) through the transparency equals only one-hundredth the illuminating intensity (I_0); $I_T(\text{black}) = I_0/100$. If we substitute this value into the expression for photographic density, we find that $D(\text{black}) = 2$. Similarly, let white be the case where the transmitted intensity equals the illuminating intensity; $I_T(\text{white}) = I_0$. This gives the result that $D(\text{white}) = 0$. Thus, the total range in the transparency for this example, would be $D(\text{black}) - D(\text{white}) = 2$. Now to generalize, we note that the total dynamic range in the image is ($g = 2$ in the previous example); $D(\text{black}) - D(\text{white}) = g$.

So far, we have specified the number of shades of grey in an image as well as defined the photographic densities corresponding to black and white and thus, the total range in the transparency. These are very useful concepts because they give us considerable improvement in control of the design of the simulated radar image which is the output product of the model we are developing. Before discussing calibration of an image, we incorporate these last two ideas into the model. In the final analysis, the output of the radar simulation model will be a shade of grey (greytone) for each pixel in the image. Thus, call the final model the greytone equation and use the symbol (G_R) to denote it. Using the previous discussions, the greytone equation can be seen to be related to Equation (II) as follows:

$$G_R = \left(\frac{2^N - 1}{g} \right) D \quad 0 < G_R \leq 2^N - 1 \quad (\text{III})$$

where the g is the simulated radar gain, selected to produce the desired black/white relationships, 2^N is the number of greytone, and D comes from Equation (II).

We're uninterested in intermediate products, what we want is the final result. That is, we want to produce a positive, not a negative, of the input data. Let's see if this expression, Equation (III), gives us the desired result. A target having a very high return power, Equation (II) should be white in the final image. Specify white in the output of the computer to be the case where the computer word is all one's (i.e., the value of $2^N - 1$ and black to be all zeroes (i.e., the value of 0). If the real system were going directly to film with the radar signal, then high intensity incident on the film during exposure would be black in the developed transparency. Let the simulated radar gain equal 2 ($g = 2$) then black has a photographic density of $D(\text{black}) = 2$. Substituting this value into Equation (III) gives immediately $G_R = 2^N - 1$, which is exactly the case we specified for white in the computer output. Thus, a target having high return power will be associated with white in the output of the computer program; just exactly as we desired. Similarly, a target having a very low return power would not expose the film. This means that the developed transparency would be white. White in a transparency has a photographic density of $D(\text{white}) = 0$. Substituting into Equation (III) gives $G_R = 0$, which is exactly what we wanted the output of the computer program to be for a low return power (black) target.

Now, we return to calibration of the image. Let's say we want to specify the greytone value and return power for a single point in the image. We will call this a calibration point and subscript Equation (III) with "c", standing for calibration, as follows: $G_{R_c} = \left(\frac{2^N - 1}{g}\right) D_c$.

Having specified the calibration point, normalize all the other pixels in the image relative to this one. Let the greytone of any other point in the image be given by Equation (III): $G_R = \left(\frac{2^N - 1}{g}\right) D$. The difference between this pixel and the calibration point can be seen to be $(G_R - G_{R_c}) = \left[\left(\frac{2^N - 1}{g}\right) D - \left(\frac{2^N - 1}{g}\right) D_c\right]$. This can be rewritten as $G_R = G_{R_c} + \left(\frac{2^N - 1}{g}\right) (D - D_c)$. Upon

substituting Equation (II), as appropriate, for D and D_c , we get the final greytone equation:

$$G_R = G_{R_c} + \left(\frac{2^N - 1}{9} \right) \left\{ \gamma \log_{10} \left[\frac{P_T G^2 \sigma^0 A R_c^4 \lambda^2}{P_{T_c} G_c^2 \sigma_c^0 A_c R_c^4 \lambda_c^2} \right] + \gamma \log_{10} \left[\frac{M}{M_c} \right] + \log_{10} \left[\frac{K}{K_c} \right] + \gamma \log_{10} \left(1 + \frac{RN}{\sqrt{N_s}} \right) \right\} \quad (IV)$$

All the terms are defined in Section (1.4).

This greytone equation is quite an important result. Look at it for a minute and see how it works. First, note that all the parameters belonging to the calibration point are subscripted with a 'c' and all parameters belonging to the pixel for which the greytone is to be calculated (all other points in an image) are unsubscripted. We want to use the greytone equation to calculate the greytone for the pixel which we chose as the calibration point as a check. Let's see what we get. All parameters, for this point, will be subscripted with 'c' giving $G_R = G_{R_c} + \left(\frac{2^N - 1}{9} \right) [\gamma \log_{10} (1) + \gamma \log_{10} (1)] = G_{R_c}$; just exactly the right result (this is so because $\log_{10} (1) = 0$). To check other points requires a few more assumptions. Let's use the interim result $G_R = G_{R_c} + \left(\frac{2^N - 1}{9} \right) (D - D_c)$ for this. Let's assume $D_c = 1$ and $G_{R_c} = \frac{2^N - 1}{2}$; these are reasonable values with which we assign the middle greytone to the middle of the photographic density range when the simulated radar gain is 2.

Now, what greytone value do we get for a low return power (black) target? Recall that a low return target means that the transparency will have a photographic density of zero. Substituting, gives $G_R = G_{R_c} + \frac{2^N - 1}{2} (D - D_c) = \frac{2^N - 1}{2} + \frac{2^N - 1}{2} (D - 1) = \frac{2^N - 1}{2} + \frac{2^N - 1}{2} (0 - 1) = 0$; which is exactly what we wanted the output of the greytone equation to be for a low return power target. Similarly, a high return target means D (black) = 2. Substituting, gives $G_R = \frac{2^N - 1}{2} + \frac{2^N - 1}{2} (D - 1) = \frac{2^N - 1}{2} + \frac{2^N - 1}{2} (2 - 1) = 2^N - 1$, which, again, is exactly the right greytone output for a high return target. These results are general and are independent of the selection for the various calibration

values; the absolute values will certainly change upon choices for calibration values but the qualitative arguments about high intensity and low intensity targets, relative to calibration values, are valid.

Any target having a return power higher than that which results in $D = 2$ for $g = 2$ will also be assigned a greytone of all ones ($G_R = 2^N - 1$). Likewise, any target having a return power lower than that which results in $D = 0$ will be assigned a greytone of all zeroes ($G_R = 0$). Thus, just as in the real radar system, signal compression occurs in the simulation model for very high return power targets and for very low return power targets. The uncompressed dynamic range of radar signal in the simulated radar image, defined by the g in the denominator of Equation (IV), can be found from our earlier definitions of what represented black and white. Recall that if $D(\text{black}) = 2$ and $D(\text{white}) = 0$, then, the range is seen to be 20 dB [This can be seen by noting that the range $I_T(\text{black})[100] = I_0$, and $I_T(\text{white}) = I_0$, which gives, after subtraction, $I_T(\text{black})[100] = I_T(\text{white})$. Or, $\frac{I_T(\text{white})}{I_T(\text{black})} = 100$ which in decibels is $10 \log_{10} \left[\frac{I_T(\text{white})}{I_T(\text{black})} \right] = 10 \log_{10}(100) = 20 \text{ dB}$]. The dynamic range of photographic film over which the transfer function (γ) is linear is typically 20 dB. Thus, it can be seen that if the simulated radar gain term is set equal to 2 ($g = 2$) in the greytone equation, this results in 20 dB of radar signal being mapped into the 20 dB available in film. This is a one-to-one mapping. By selecting g as desired, any other mapping can be implemented. This term, the g in the denominator of Equation (IV), essentially sets the gain of the simulated system.

When we select a value for g and the greytone value (G_R) return power (σ_c^0) for the calibration point, we specify which part of the dynamic range of the radar signal we are recording on film. The selection of g effectively sets the gain by determining how much of the dynamic range of the radar signal is recorded on film and selection of G_R and σ_c^0 set the bias by setting the brightness level on film of a point in the dynamic range of the radar signal. Therefore, appropriate selection of the gain and bias terms result in

calibration of the simulated radar image; the desired dynamic range and desired portion of the radar signal dynamic range will be recorded on film.

Equation (IV) is what we call the graytone equation and it represents the basic building block for our simulation model as we have implemented it on the digital computer. Since we selected to calibrate the image by specifying a point in the image, the film exposure and development constant (K) in Equation (II) dropped out of Equation (IV) [$\log_{10}(\frac{K}{K_c}) = \log_{10}(1) = 0$; the same image includes both the calibration point in addition to every other pixel, thus, $K_c = K$]. Also, if a linear radar receiver transfer function is being simulated, then the term incorporating the ratio of transfer functions will drop out of Equation (IV) for the same reason. If the receiver being modeled is nonlinear, then, of course, this term must be included.

This completes our discussion of the development of the graytone equation. This is the expression implemented in our Point Scattering Radar Image Simulation computer programs. Of course, as previously mentioned, the graytone equation is not the complete model; just the final expression. The complete model includes software realizations of algorithms for calculating shadow, layover, range compression, angle of incidence, local angle of incidence, range, local slope of the terrain, and more. Development of these algorithms is beyond the scope of this section; see the appropriate sections and appendices in this report.

III. Radar Simulation

In previous sections we have discussed radar systems and have developed the greytone equation, Equation (IV): We have not completely derived the Point Scattering Radar Image Simulation Model, that being beyond the scope of the discussions in this section. In this section, we are going to describe how we use the simulation model and show how it is altered to the proper configuration representing a specific radar system. We are going to discuss the ground truth data base and the major problems of constructing, storing, and using them. We shall outline the use of backscatter data; where we get it, where it comes from, what it means, and how we use it. Finally, we are going to sketch image processing difficulties as they apply to radar simulation.

The block diagram shown in Figure III is a simplistic representation of radar simulation; it represents our approach to radar simulation utilizing an implementation of the point scattering method on the digital computer. This figure shows both the input requirements of our model and the output product. As can be seen, the radar simulation program requires three basic kinds of input data: (1) Radar parameters; (2) Ground truth data base; (3) Radar return data $-\sigma^0$. The radar simulation program (called the Point Scattering Radar Image Simulation Model) contains an implementation of the Greytone Equation (IV). It contains explicit provisions for calculating the return power, shadow, layover, angle of incidence, range compression, etc. (details are available in Sections 2, 3, and 4). Given these capabilities designed into the software representation of the Point Scattering Radar Image Simulation Model, and given the necessary three kinds of input data to the model, the computer program forms a simulated radar image.

When a new application for radar simulation is identified, a fairly involved chain of events is followed. Very briefly, this chain is started with specification of the radar which is to be modeled, and identification of the target site on the earth for which a simulated radar image is to be produced. Specifications of the radar defines a number of

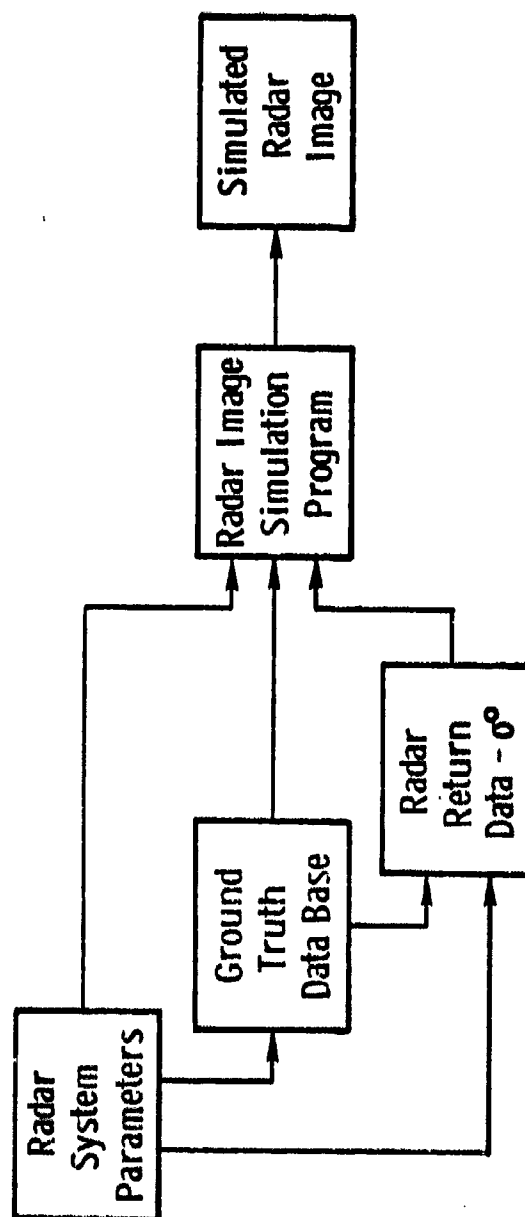


Figure III. Fundamental Block Diagram - Simulation

parameters which are essential to further work. Identification of the target site allows preliminary work on the data base to be started. This preliminary work involves identifying, locating, and acquiring source data, such as high-resolution aerial photographs and maps, which are essential to construct the data base.

The data base is a major input requirement of the radar simulation program. Since the radar simulation model has been implemented on the digital computer, the data base must be in digital format. The data base is a digital representation of the different features and the elevation variations of the terrain present in the target scene. Typically, the data base consists of a digital matrix containing four dimensions. These four dimensions are the range and azimuth coordinates, elevation, and radar backscatter category of each point in the scene. It is this matrix upon which the simulation program operates to calculate such parameters as look-direction, range, angle of incidence, shadow, layover, range compression, etc. After calculating these parameters, the simulation program obtains from the data matrix the radar backscatter category of each point in the scene. At this point, the simulation program is finished with the data base. The program now requires backscatter data (σ^0); the third major input requirement of the simulation program. Upon specification of the transmitter frequency and transmit/receive polarization, and upon identification of each of the different backscatter categories in the target scene (from the data base work), backscatter data can be obtained. The backscatter data measure the transmitted pulse and ground interaction and determine the fraction of power reradiated back to the radar. These data are obtained from empirical data banks, or from the literature, or from appropriate theoretical scattering models. Regardless of where obtained, the simulation program requires the σ^0 data specified by the data base as an input; then, using the parameters calculated and these σ^0 data, the simulation program produces the desired output: A simulated radar image of the desired scene which represents the operating characteristics of the specified radar.

This description completes a very brief overview of our approach to radar simulation. The attempt in this discussion was to define the major simulation components and to illustrate the relationships and interrelationships between the major components. Now, we would like to go one step further and develop (by verbal arguments), in a little bit more detail, the simulation model and its input requirements.

Review the radar simulation model illustrated in Figure III. Upon defining a new radar system which is to be modeled for simulating radar images, the radar system operating parameters and characteristics are specified. Some of the more important of these characteristics are (1) Transmitter frequency; (2) Transmitter pulse length; (3) Transmit/receiver polarization; (4) Antenna pattern; (5) Antenna beamwidth; (6) Receiver transfer function; (7) Image medium; and (8) Radar Type and Image format (SLAR, PPI, SAR, etc.). As shown in Figure III, these parameters are input to the radar image simulation program. They are used to set-up the Point Scattering Simulation Model computer programs for the specific characteristics of the radar system being modeled and some are used explicitly in the greytone equation. The transmitter pulse length is used to identify the radar resolution in the range direction. The antenna beamwidth is used to specify resolution in the azimuth direction. Together these parameters specify the size of the radar resolution cell, data used in both the greytone equation (parameter A in Equation (IV)) and in the construction of the data base for the desired scene. More details about resolution are presented in Section 1.4. The transmitter frequency and transmit/receive polarization are used both in the greytone equation (parameter λ ; $\lambda = \frac{c}{f}$) and in obtaining radar return data; they specify two of the major parameters of σ^0 .

The antenna pattern is very important. If real pattern data are available and the application warrants its use, these data are implemented in the computer program to convolve the antenna pattern with the return power data. If the data are not available or if the application does not warrant the additional computer resources required to convolve

these data, a symbolic antenna pattern may be used. Such a pattern would be the common $G=G_0 \sec^2 \theta$ where G is the antenna gain term of Equation (IV), and θ is the angle of incidence as shown in Figure I). At any rate, the function of the antenna pattern (or gain), as previously noted, is to account for the directivity of the antenna used by the real system, and is an important simulation parameter.

The receiver transfer function can have a significant impact on the radar simulation effort. If circumstances warrant inclusion of the actual receiver transfer function, it replaces the parameter M , in Equation (IV). This is another parameter which may have a major impact on the required simulation computer resources, especially if the transfer function is non-linear. If it is linear, then, except for super-critical applications, it can be calibrated out of the simulation model.

If the image medium is to be different from photographic film, then the model, Equation (IV), needs to be altered accordingly.

The radar type and image format impact both the radar simulation program and the data base construction. The model and data base need to be set-up to simulate either the rectangular coordinate system image format of a SLAR or the polar coordinate image format of a PPI. Also, in the event it is desired to model a SAR (Synthetic Aperture Radar) this specification would impact, in addition to major considerations in the model and data base, collection of σ^0 data.

At this point we have discussed the ramifications to radar simulation of specifying the radar system parameters for a new application. As shown conceptually in Figure III, specification of these parameters impacts both the data base, σ^0 data, and the simulation model. Assume that the necessary alterations are made to the computer program such that these parameters are properly implemented. It is not our purpose here to discuss the details of how these alterations are made. Suffice it to say that they are made and details can be found in Sections (2.0), (3.0), and (4.0). Having specified the parameters and implemented them in the computer program, the radar simulation program is ready to form simulated radar images.

To do this, we need to acquire two additional pieces of data: (1) Ground truth data base and (2) σ^0 data.

After specification of the radar system and simulation application comes identification of the simulation target scene. This is the physical area on the earth of which we are going to form simulated radar images. To produce a simulated radar image of this specified area of the earth, the radar simulation program requires two kinds of information about the features and properties of the earth in that area. First, the radar simulation program requires a ground truth data base which contains the relative position, the elevation, the geometry and backscatter category of each point. Second, the program requires backscatter data for each category identified to be in the simulation target area. If those data are available, the Radar Simulation Program can then be run and the desired simulated radar image can be formed.

Development of the ground truth data base is a very large problem facing radar simulation. Since we implement our radar simulation program on the digital computer, the ground truth data base must be in digital form, compatible with the computer. The data base can be considered to be a digital model of the physical, geometric properties of the ground. This digital model, as we develop it, is typically a four-dimensional digital matrix; two dimensions specify the location of each ground point, another specifies the elevation of each point, and the fourth specifies the backscatter category of each point. Construction of this digital ground model is a difficult, time-consuming problem.

After specification of the simulation site (data base area) and radar parameters, work can be started on construction of the data base. The first thing we do is locate and obtain high-resolution photographs, maps, and, possibly, other imagery (such as IR - Infra-Red - or radar) of the site taken during the same time of year as the simulated imagery is to represent. Then we use the radar parameters to determine the size of each ground point that the ground truth matrix represents; that is, we use the radar parameters to determine the resolution we will build into the data base.

Once the source imagery (photos, maps, etc.) have been obtained and the resolution determined, work on construction of the data base can be started. A photo-interpreter uses the source imagery and his knowledge and intuition of radar images of the same frequency, polarization, and resolution being modeled to construct a data base map of the area. The data base map is typically drawn by hand; major features may be traced from either maps or photos, or both, depending upon the relative scales and distortions of the various sources. Construction of this hand-drawn data base map is a major effort requiring judgment, accuracy, and knowledge of the area. A major goal pursued in the development of the data base map is reduction of the scene to the collection of the least number of homogeneous regions possible. We use our experience and intuition to decide where a new backscatter category is necessary and then extend the new category over the maximum area that is possible. For instance, large forested areas may be considered homogeneous even though the area may consist of many different kinds of trees. A break in the tree cover would, however, be cause for adding another boundary and category because of the great dissimilarities between trees and most other categories. Similarly, other vegetation covers would be considered homogeneous over as large an area as possible. New categories are not added unnecessarily, for each new category complicates later phases of construction of the data base. This can be seen by recognition of what must be done to convert it to a digital matrix; it must be digitized.

At this point, the data base map is, typically, a symbolic drawing (category map) of the simulation target scene. This symbolic category map is a line drawing of the boundaries outlining major features present in the area (such as boundaries separating forests and vegetation, or bare soil; or boundaries separating vegetation and bare soil; or boundaries separating different backscatter types of vegetation; or . . .). The next phase of construction is digitization of the category map. We typically use a large table digitizer and a human operator to digitize the boundaries in the category map. The human traces each boundary with the cursor of the table digitizer and the computer attached to the digitizer table periodically samples and records the position of the cursor. As a new boundary trace

is started, the operator specifies to the computer what categories this boundary separates. As might be imagined, boundaries do not always simply divide two categories; three, and even four, categories are frequently divided at a single point. This, of course, creates problems in keeping straight exactly what a boundary represents. More importantly, this multiple category problem is a source of real problems later when converting these digital boundary data into a digital matrix.

After completion of the digitizing task, we have a digital magnetic tape containing the sampled position points, all stored serially (consecutively), for each boundary in the category map. Each record on the tape records the position of a boundary point and the categories being separated by the boundary. These serial boundary data must now be made into a digital matrix. The desired digital matrix will be completely filled-in, as opposed to just having boundaries present. The size of the digital matrix is determined by the resolution built into the category map; one cell in the matrix represents the resolution size on the ground (e.g., if the radar resolution element is determined to be twenty-five feet, then each point in the matrix represents, at most, twenty-five feet on the ground; finer resolution may sometimes be desired). Thus, the task facing us at this point is to read the serial boundary data into the computer; sort them, for instance, by their x-coordinates; and then order the y-coordinates for each constant x-dimension. In this way, the boundary data points can be stored in the correct matrix cell; what is stored is the categories being separated by each point, not the x- and y-coordinates of each point, for that information is implicit in the position of the matrix cell. At the completion of this activity, we have a digital matrix which is a symbolic map of the ground. Each cell in this matrix represents a specified number of feet on the ground and lists the backscatter category of that point. One last task remains to be accomplished before we have a completed ground truth data base: We must obtain elevation data for the scene and add it to this matrix.

Fortunately, for the data bases we made under this contract, digital elevation data were provided to us by ETL (Engineering Topographic Laboratories, U.S. Army, Fort Belvoir, Virginia). One digital magnetic tape of elevation data was provided per standard 7 1/2' U.S.G.S. (United States Geological Survey) Quadrangle map of the target scene. The desired target scene covered six of these maps, thus, to obtain elevation data for use in the data base, we had to extract the appropriate set of data from each tape and then merge them into one orthogonal matrix. This task of merging alone required much effort because each map had been digitized independently of every other with no apparent thought given to combining data from different maps. We combined these elevation data provided us into one digital matrix and then merged the category and elevation matrices into one, new four-dimensional matrix which became the required ground truth data base for the specified target scene. This task was made easier by judicious selection of the size of ground spot each matrix cell represented (the size was made identical for both the category and the elevation matrices) and of the coordinate systems of both matrices (they were both set-up to be in the same coordinate system). Upon completion of this activity, the ground truth data base was ready for input to the radar simulation program. The data base is a digital model of the backscatter category features and elevation variations present in the target scene.

One last task remains to be done before we are ready to use the simulation model to form a simulated radar image of the target scene; we must obtain the backscatter data for each category included in the ground truth data base. Recall that the backscatter parameter, σ^0 , determines how much of the transmitted power which illuminates a point on the ground will re-radiate back to the radar. The parameter, σ^0 , models the transmitted energy interaction with the ground.

Acquisition of σ^0 data is a major obstacle facing radar simulation. A lot of empirical (measured) σ^0 data presently exist in the literature and, in particular, in an agriculture/soil moisture data bank being developed at the RSL (Remote Sensing Laboratory). These data, as much as there are,

represent just the first step. Much more σ^0 data needs to be collected for many more of the variables (recall that σ^0 varies with many parameters, such as frequency, polarization, vegetation type, soil type, soil moisture, season, etc.). Empirical data are not enough. It is not reasonable to expect to measure σ^0 for every conceivable variable in the terrestrial envelope in a finite period of time. Theoretical electromagnetic scattering studies need to be developed to extend and extrapolate these measured data for the cases which are not measured. There exists a genuine need for these theoretical data. Without these data, the concept of radar simulation is basically limited to what can be done with the empirical data which are available. Enough philosophy for now.

We search the literature and examine our data bank for empirical σ^0 data we can use for the radar frequency and polarization, and for the categories included in the ground truth data base. We also examine existing scattering models to determine their potential applications for obtaining σ^0 data for some categories. We use our knowledge of the scattering properties of the kinds of categories identified in the data base to aid this search. It may not be possible to find exactly the data for a particular category, but it may be reasonable to substitute another σ^0 category which is available because our knowledge and experience leads us to conclude they are "similar" at the desired frequency and polarization. We recognize that this is not being rigorous but we are making-do with what is available. In fact, far from making-do, we are being immensely successful. After obtaining the σ^0 data we plan to use for each data base category, we fit curves to these data to put them into a form compatible with the simulation program.

Typically, empirical σ^0 data are presented in the data bank and literature for each frequency, polarization, and category, for only a few angles of incidence. Our simulation program requires σ^0 data to be input as σ^0 versus angle of incidence (θ) for each frequency, polarization and category. We fit a best curve to the σ^0 versus θ trend for each category and then use these curves to interpolate for other points. Frequently, the σ^0 data

we wish to use does not span the range of angles of incidence we need. In those cases, we must complete the trends, calling upon our knowledge and experience with those kinds of categories. At this point, the σ^0 data have been obtained and put into the desired computer-compatible format. All of the work preliminary to forming simulated radar images have been completed. We are finally ready to use these data for forming images.

This completes the discussion of the simulation model, how it is altered to the configuration of a specific radar system, its input data requirements, what these data are, and how we obtain them. All necessary requirements have been satisfied to produce radar image simulations using the operational characteristics of the radar being modeled and of the specified test site. It remains only to run the radar simulation program. This is a good point to halt this discussion of an overview of our approach to radar simulation embodying the Point Scattering Radar Image Simulation Model. Additional specific information about any facet of our model or approach can be obtained by reference to the rest of this document.

We would like to complete this section by listing a few problems associated with radar simulation and postulating approaches to solutions, or future studies to be conducted. First is the problem of trying to manipulate very large data bases in the digital computer. Vast amounts of data must be processed for all but trivial applications of radar image simulation. As presently structured, data bases consist of at least one point in a matrix for each pixel (picture element) in the final simulated radar image. This means that most data bases for operational systems are exceptionally large (more than ten million points) and even the most trivial image handling is inordinately complex. Simple things such as rotations of data bases to alter the look direction (flight line) are tremendously time consuming and expensive. It is recommended that techniques for both data compression and alternate methods for information storage and retrieval be investigated. The great potential value of radar image simulation for

many present and future applications argues that this investigation needs to be conducted.

Another major area where significant improvement is necessary is the area of data base construction: Feature extraction is the proper term. The techniques we used to produce our data bases are basically manual techniques. The utility and versatility of radar image simulation is dependent upon automating the problems of ground truth data base construction, of feature and elevation data extraction. Classical techniques for feature extraction are manual techniques. Typically, a photo-interpreter scans the intelligence data and draws upon his interpretation experience to decide what information to transfer manually to the data base under construction. These decisions are made with as few digital computer image enhancement techniques as possible. This reticence to use available enhancement routines is caused, in part, by the very nature of the automatic routines. They are not generally applicable to any but specific, well-structured, test cases. In addition, use of these techniques requires that the interpreter also be a computer expert. Moreover, the interpreter loses control and visibility of what he is trying to accomplish when he enters the computer world of automatic land-use classification, or pattern recognition, or region definition, or ad infinitum. These reasons have serious ramifications for feature extraction and consequently for data base construction; they cost money. They cost money in the sense that it takes a much longer time to extract the features manually for a data base than might otherwise be necessary; data are manipulated by hand and the best information may not be obtained.

Clearly, a tremendous improvement of the product developed, resources expended, and time required could be obtained if a workable marriage between computer and interpreter could be arranged. The computer is very good at manipulating vast amounts of data in short periods of time; the human is not. The human is beyond comparison when it comes to drawing upon learning experience to make decisions. The computer excels at clearly defined repetitive tasks, at statistical analyses, at image enhancements.

A cooperative approach in which the human is used to make decisions and guide the processing direction of the software, and the computer is used to manipulate the data rapidly and easily and to remove the drudge from the human would be optimal - optimal in the sense of maximizing the return for resources expended and minimizing the time and effort. This cooperative approach is called interactive feature extraction or automated feature extraction (not automatic feature extraction since this is impossible with the state of the art available today).

The concept of interactive feature extraction uses the human for his specific strengths and the computer for its specific strengths. In interactive feature extraction, the computer is used to display, enhance, manipulate, and otherwise aid the human interpreter as he performs his function. Viewed another way, the human is used to make decisions and to guide the computer in real-time as the programs run. Interaction can be accomplished by giving the interpreter a few basic tools with which to communicate his decisions to the computer; a keyboard for commands, a joystick for direct specification, and an interactive graphics display are probably the minimum to be provided. Given these capabilities, the data base can be built directly as the feature information is processed and decisions are made. Boundaries separating different regions can be specified directly by the interpreter and, while the human is analyzing the next problem area, the computer can build the symbolic data base immediately and display the results. Depending upon the level of sophistication of the interactive software and of the computer and display complex, tremendous savings of resources and improvements in efficiency and quality of the finished product are hypothesized. Given an interactive feature extraction system, special emphasis could be built-in to maximize the use of the intelligence data normally available from which to define the geometry, dielectric properties, and elevation data which are required to support radar image simulation.

The last philosophy to be discoursed upon here concerns the need for empirical backscatter data and theoretical scattering models to support radar simulation. Backscatter data needs to be collected for as

much of the terrestrial envelope at as many microwave frequencies and polarizations as required by the uses for which simulated radar images are desired. If radar image simulation is going to be used increasingly, reliance on existing small programs and the mission objectives of many agencies to collect data for specific programs is ill-founded. It will require many years and good luck for this need for backscatter data to be fulfilled in this way.

A program to collect the data required by the radar image simulation problem is needed. Radar image simulation needs empirical backscatter data for a multitude of frequencies and polarizations of all classes of terrestrial features. These data should be collected for as many seasonal variations of each category as is practical. In addition to collecting the data, the program must also process the data. These data will have to be organized, catalogued, and filed.

Empirical data are not enough. Theoretical electromagnetic scattering studies should be developed to extend and extrapolate the measured data for the cases which are not measured. It is not reasonable to expect to measure backscatter data for all permutations of the variables. There are too many combinations. This is where theoretical studies show their value.

These data and studies are essential to support present and future radar simulation applications. It is our belief that radar simulation will be an important engineering tool in future defense programs. If this becomes the case, these data and studies will attain high importance and priority. We possess, today, the opportunity to exercise a little foresight by starting this work.

1.0 SUMMARY AND RESULTS

1.1 Introduction

A Radar Simulation Study was performed to test the Point Scattering Radar Image Simulation Model developed and reported in previous work^{1,2}. An implementation on the digital computer of the Point Scattering Model was applied to three specific problems in this study, and the work performed and results obtained are reported in this document. The three specific applications tested in this study are: (1) SLAR (Side-Looking Airborne Radar) Model Validation; (2) PPI (Plan-Position Indicator) Radar Model Validation; (3) Terminal Guidance Applications. In addition to the implementation on the digital computer and testing of these three applications of the simulation model, much effort was expended in peripheral activities required to support the main efforts. Principle of these was data base construction with emphasis on feature extraction methods and techniques. Since these activities are of critical importance to successful implementation of radar simulation models and to successful utilization of these models, the contents of this document are extended to report these support activities, also.

The scope of the work performed in the Radar Simulation Study was limited by budgetary and manpower resources considerations to testing the Point Scattering Radar Image Simulation Model against one specific geographical area. The three applications (SLAR, PPI, and Terminal Guidance) of the simulation model were each tested against this one area. The area selected for this test of the simulation model was the topographic region in the states of Tennessee, Alabama, and Mississippi, centered on the northwest corner of the powerhouse at the Pickwick Landing Dam,

¹ Holtzman, J. C., V. H. Kaupp, R. L. Martin, E. E. Komp, and V. S. Frost, "Radar Image Simulation Project: Development of a General Simulation Model and an Interactive Simulation Model, and Sample Results," TR 234-13, Remote Sensing Laboratory, The University of Kansas, Feb., 1976.

² Holtzman, J. C., V. H. Kaupp, and J. L. Abbott, "Radar Image Simulation Project," TR 234-15, Remote Sensing Laboratory, The University of Kansas, September, 1976.

Tennessee. The SLAR and PPI validation work was limited to forming a sequence of radar image simulations from two different look directions of selected subregions of the Pickwick test site and comparing these simulated radar images to real images (of the same regions) having the same look directions. The terminal guidance work was limited to producing reference scenes of the Pickwick site from one altitude for input to the Correlatron.* The data base construction/ feature extraction work was limited to preparation of two data bases of the Pickwick site: (1) Data base for SLAR and PPI validation work; (2) Data base for Terminal Guidance work.

The Point Scattering Radar Image Simulation Method rigorously models the relationships and interrelationships of the radar system, ground scene, and image medium. The general model, as reported and implemented on the digital computer by Holtzman, et al.^{1,2} can be used in a wide variety of applications. It can be used to simulate the image products of different radars and the radar return properties of different scenes. Both SLAR and PPI image formats can be simulated. The general simulation model is mathematically rigorous and, therefore, is applicable to simulate the image products of an imaging radar for any scene providing only that the transfer function be known (and modeled) and providing that the geometric and dielectric properties of the ground scene are adequately modeled.

The simulation model incorporates the operating parameters (frequency, polarization, resolution, scan format, etc.) and transfer

¹ Holtzman, J. C., V. H. Kaupp, R. L. Martin, E. E. Komp, and V. S. Frost, "Radar Image Simulation Project: Development of a General Simulation Model and an Interactive Simulation Model, and Sample Results," TR 234-13, Remote Sensing Laboratory, The University of Kansas, Feb., 1976.

² Holtzman, J. C., V. H. Kaupp, and J. L. Abbott, "Radar Image Simulation Project," TR 234-15, Remote Sensing Laboratory, The University of Kansas, September, 1976.

* Correlatron is the name of a two-dimensional cross-correlation measuring device manufactured by Goodyear Aerospace. The ETL has a Correlatron installed in a test configuration.

function of the system whose image products are to be simulated. The model of the system operates on a representation of the terrain that is a digital model of the ground scene. The ground scene model (hereafter referred to as a ground truth data base or, simply, as a data base) required in this work was a digital matrix which specified the backscatter category (radar return category) and elevation of each point on the ground in the scene. The data base contains all the basic scene specific data the simulation model requires. The data base provides the necessary information for the simulation model to calculate all the imaging parameters (range, angle of incidence, slope, local angle of incidence, etc.). It also specifies the backscatter category of each point on the ground.

To complete the calculation, the model requires backscatter data for each category identified in the scene. Typically, in all the simulation work using the Point Scattering Model, this data requirement is satisfied by theoretical scattering models, or by empirical differential scattering cross-section (σ^0) data. The empirical data come either from existing data banks such as the agricultural/soil moisture backscatter data bank being developed at RSL⁴ or from the literature. Radar images, themselves, have not been tapped as a source for these data for several reasons: (1) The necessity of calibrating the receiver response; (2) Most work done has been aimed at establishing the validity of the model and techniques, and it was deemed improper to use a radar image of a particular backscatter category to "simulate" that same category. After presenting the simulation model (of a specific radar) with both the data base (of a specific scene) and backscatter data (for the categories in that scene) the model calculates the fraction of energy reradiated back to the radar, processed by the receiver, incident on the image medium (film), and finally, the density, (transmittance)

⁴ Bush, T.F. and F.T. Ulaby, "Fading Characteristics of Panchromatic Radar Backscatter from Selected Agricultural Targets," IEEE Trans. Geosci. Electron., Vol. GE-13, October 1976, pp. 149-157.

between black and white (called greytone), of each pixel (picture element) in the image (simulated radar image of that scene).

The Point Scattering Radar Image Simulation model is applicable equally well to scenes of terrain having little or no relief as well as to scenes having significant relief. The model is applicable over a wide range of radar resolutions. This range extends from high resolution to very coarse. The necessary provisions are only that there are enough independent scatterers on the ground in each resolution element of the radar being modeled for the averaging properties of the radar equation⁵ to hold and provided also that proper account be included in the software implementation of the model of the dependence of the image on adjacent resolution elements (resolution cells). Equally important is the necessity to model, commensurate with the radar resolution, the topography and dielectric properties of the ground from which it is desired to produce a simulated radar image. Most topography can be modeled as collections of homogeneous regions which are typically larger than the resolution element of the radar system being simulated. Regions of this type are called distributed targets.

Distributed targets are simulated very well by the point scattering method and have several very important practical considerations. They simplify the task of constructing ground truth data bases and are the basis for using empirical data banks of differential scattering cross-sections (backscatter data - σ^0) as the input data to completely specify (within the limitations of the accuracy of the data and satisfaction of the statistics controlling their use) the dielectric properties of the objects and features on the ground. Typically, for the radars of interest in this study, man-made objects and features can not be modeled as distributed targets; they are called cultural targets. Just as they cannot be modeled as distributed targets, neither are they easily simulated by the point scattering simulation method. Cultural targets

⁵ Keeves, R. G., A. Anson, and David Landen, Manual of Remote Sensing, Vol. 1, Chapter 9, American Society of Photogrammetry, Falls Church, Virginia.

are more amenable to simulation by the Area Spatial Filtering simulation method reported by Frost, et al.⁶. An optimum radar image simulation model would be a hybrid combination of the point scattering method for distributed targets and the Area Spatial Filtering method for cultural targets. However, testing and validation of the area spatial filtering method is not reported here. In this work, cultural targets have been included symbolically in the ground truth data bases and have been simulated symbolically.

Implicit in all of our previous work, whether or not explicitly stated, was the fact that the systems being modeled were "ideal". The radar system was modeled as though it were a perfect system; the antenna pattern was "ideal"; it was a collection of "perfect" homogeneous regions which ideally fit the simulation model and backscatter data requirements, plus cultural targets. These homogeneous regions reradiated energy exactly as described by σ^0 . The image medium was modeled as linear over its entire dynamic range. All of these assumptions, and more, have been made in previous work in the interests of computational efficiency. As can be seen, they are not restrictive assumptions. The results produced using these premises were generally better than if "real-world" processes had been modeled exactly. The test of a model isn't the degree to which each subcomponent matches the "real-world", but is the degree to which final results resemble the actual products of real systems. The results produced have been excellent, arguing that "perfect" systems represent a good starting point for radar simulation.

Up to now, the radar simulation work has concentrated on refinement of the model and efficient software implementations of the real processes being modeled. With the work presented in this report, the transition is made from development to validation and to application.

⁶ Frost, V. S., J. L. Abbott, V. H. Kaupp, and J. C. Holtzman, "A Mathematical Model for Terrain-Imaging Radar and Its Potential Application to Radar Image Simulation," TR 319-6, Remote Sensing Laboratory, The University of Kansas, November, 1976.

Implicit in all our previous work, whether or not explicitly stated, was the fact that the systems being modeled were "ideal". The radar system was modeled as though it were a perfect system; the antenna pattern was "ideal" with no distortions, degradations, or sidelobes, and the receiver was linear. The ground scene was modeled as though it were "ideal"; it was a collection of "perfect" homogeneous regions which ideally fit the simulation model and backscatter data requirements, plus cultural targets. These homogeneous regions reradiated energy exactly as described by σ^0 . The image medium was modeled as linear over its entire dynamic range. All of these assumptions, and more, have been made in previous work in the interests of computational efficiency. As can be seen, they are not restrictive assumptions. The results produced using these premises were generally better than if "real-world" processes had been modeled exactly. The test of a model isn't the degree to which each subcomponent matches the "real-world", but is the degree to which final results resemble the actual products of real systems. The results produced have been excellent, arguing that "perfect" systems represent a good starting point for radar simulation.

Up to now, the radar simulation work has concentrated on refinement of the model and efficient software implementations of the real processes being modeled. With the work presented in this report, the transition is made from development to validation and to application. With this transition comes the necessity for sophistication and, where required, the system configuration being simulated is included in the model. The goal of the work reported in this document has been to test and validate the point scattering simulation method by direct applications of the model to specific scenes and comparison of the results with real imagery of the same scene. All activities have been directed toward attaining that goal.

1.2 Summary of Work

Successful completion of the Radar Simulation Study required coordination of many different activities and interdisciplinary cooperation. Many diverse talents were required by the different facets of the work.

These talents were found in geographers, electrical engineers, botanists, and computer scientists. The results produced are a tribute to the team of individuals who, together, performed this work. The complexity of the work performed is shown in Figure 1.

This figure shows the interrelationships among the types of work done and it shows the flow of work. Five different kinds of work are shown in this figure. First, the effort required to develop data bases is shown conceptually in the lower right hand corner of the figure. Next, in a clockwise direction, is the work performed to obtain the backscatter data which were required to model the radar return properties of the ground. In the lower left hand corner, the study of automated and interactive feature extraction techniques is shown. Fourth, in the upper left hand corner, is the modeling and software implementation work. Fifth, in the upper right hand corner, is the work performed to produce the radar image simulations and validations, and the Correlation tests. Figure 1 is a conceptual block diagram of all the work performed and the relationships between disciplines and types of work. This figure is designed to give a mental picture of the work and services provided under this contract so that in succeeding sections, when a task is referred to, a mental image of that task and its relationships to other tasks is visualized. The figure is not designed to impart more information than that. In particular, this report is not structured according to Figure 1. The report is structured according to results, not work performed. In fact, it will be seen in the sections that follow that most of the work shown in Figure 1 is required to produce each different set of results. Thus, as a conceptual model, Figure 1 represents the flow of work for each task performed.

Recall that the purpose of the work performed under this contract was to apply the Point Scattering Radar Image Simulation Model to three specific applications: (1) SLAR Model Validation; (2) PPI Radar Model Validation; (3) Terminal Guidance Applications. The report is organized to report the results of these three tests plus the data base construction/feature extraction work. Since the report is organized along these four distinct activities, the work is summarized also along them.

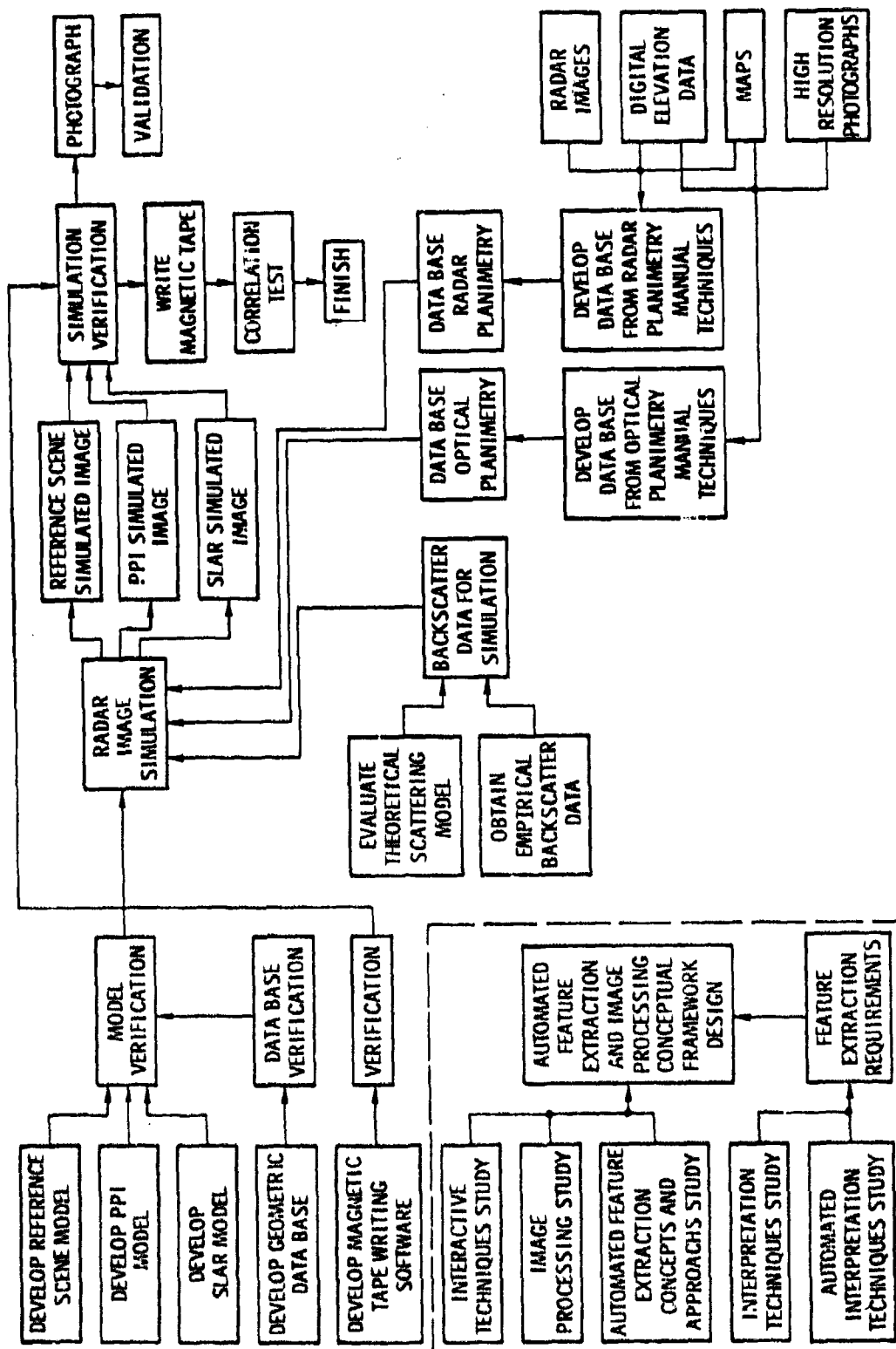


Figure 1. Conceptual Block Diagram and Flow of Work Performed

1.2.1 Summary of Work - SLAR Validation

The general Point Scattering Radar Image Simulation Model was validated for the specific case of a SLAR having medium resolution. The simulation model was modified as required to simulate the image products of a SLAR. Normally, when modeling a system, calibrated system data and transfer functions are used to develop the characteristics which approximate "real-world" events. In this case this was undesirable. For validation, it was desirable to model a "perfect" system, for the best results obtainable. Modeling a "real" system (i.e., one having performance deficiencies) would only degrade the results produced. To stress the point, we want to differentiate between validating the basic simulation method (which is what this task is all about) and validating the model of a specific radar (which can easily be done after this first step). Therefore, the general simulation model was transformed to the system configuration of a "perfect" SLAR: Antenna pattern, transmitter, receiver, ground and film were all assumed to be "ideal".

For validation purposes, the antenna pattern was assumed to have constant gain in the azimuth direction out to the "3 dB" points and to lack sidelobes. The transmitter was assumed to produce "perfect" pulses, and the receiver was assumed linear. The ground, for data base purposes, was modeled as a collection of "perfect" homogeneous regions which re-radiated energy exactly as described by σ^0 data. The film was assumed to be linear over its entire dynamic range with "perfect" exposure and development and without compression at either high or low densities within the linear portion of the dynamic range. All of these characteristics were incorporated into the simulation model and an implementation was designed for the digital computer. Within the limitations imposed by modeling a "perfect" SLAR, complete generality was retained. The digital computer program realization of this model was structured to allow rapid alterations to be made in the specification of radar, or other, parameters (so long as the modeled radar was a SLAR) and, therefore, is most useful for radar image simulation studies. This computer program, when it includes the necessary parameters for a particular radar flying at a specified altitude over a desired ground track, and when it includes the parameters of the mechanism by which the visual

record is to be produced, and when it includes the backscatter and geometric properties of the scene to be formed, becomes the vehicle for producing the simulated image products of a specific radar system. The validation of the SLAR simulation model was performed on images produced by this computer program.

A qualitative validation was performed on these results. Validation was accomplished by comparing the simulated SLAR images to real SLAR images of the same site. The format of the validation was straight-forward. A site was selected for which real SLAR imagery of satisfactory resolution could be obtained. A data base was constructed of this site for input to the SLAR simulation computer program. The data base was rotated as necessary to match the flight lines of the real imagery. Images were produced from the data base of the validation site by the simulation computer program with the model parameters set to simulate the response of a medium resolution radar having the same operating frequency and polarizations as the real system. Empirical backscatter data were used to model the dielectric properties of the distributed targets in the data base. These simulated radar images were then compared to the real images and the quality of the simulation model was qualitatively measured. The comparisons established a baseline of quality for the radar image simulation model. In short, the validation phase of the SLAR simulation model was very successful. The model produced images which compared, in general, in a superior manner with the real images. Specific discrepancies occurred. These discrepancies were generally attributable to one of four classes: (1) Features not included or incorrectly specified in the data base model of the scene; (2) Backscatter categories which cannot be modeled simply by the differential scattering cross-section, angle of incidence, and resolution cell; (3) Differential scattering cross-section data (backscatter - σ^0) not available for specific distributed targets; (4) Image processing differences between the real images and the simulation images. Items

(1) and (2) account for nearly all the discrepancies noted. These four classes of "error" are not limitations of the quality of the images which can be produced by the simulation model. They are errors of input data specification. They indicate that more input information is required, and, given these data, it is reasonable to expect the model to produce results without these errors.

In general, the comparisons were very favorable. In fact, we have noted on numerous occasions that people with real radar image familiarity and experience believed that they were seeing an image from a real system. They were surprised when told it was a simulated image produced on a digital computer. This comment speaks more eloquently for the quality of images produced by the point scattering simulation method than the attempts to objectively measure the quality. The validation work on the SLAR simulation is reported in Section 2.

1.2.2 Summary of Work - PPI Validation

The general model of the Point Scattering Radar Image Simulation Model was validated for the specific case of a PPI radar having medium resolution. The simulation model was transformed as required to simulate the image products of a PPI radar. A computer program was built incorporating the realization of the PPI radar and the model was validated in the same way that the SLAR was. Just as the SLAR model was constructed for a "perfect" radar system, so was the PPI configuration modeled after a "perfect" system. All the comments about the model, the data base, and the backscatter data made in the case of the SLAR (1.2.1) apply here.

Several differences existed, however, in the PPI validation. The principle difference is that real PPI images of the validation site did not exist. This prompted a different approach for validation, an indirect approach. Validation was accomplished by comparing the simulated PPI images to both the real and simulated SLAR images. This approach was mutually agreed upon by both the RSL and ETL in view of the lack of real comparison PPI imagery. This comparison could be performed only for small sectors of each SLAR image at a time since only a small angular range is coincident. All the basic steps outlined for the SLAR validation

were performed for the PPI validation. A number of simulated PPI images were produced from the same data base of the validation site as was used for SLAR. The only differences were caused by the necessity to convert the rectangular SLAR data base into a polar PPI data base. The simulation computer program was set-up to simulate the image response of a medium resolution PPI having the same operating frequency and polarization as the real and simulated SLAR images. Images were produced by this computer program operating on the polar data base of the validation site and using empirical backscatter data for the distributed targets. These simulated radar images were then compared to the real and simulated SLAR images of the same site and the quality of the simulation model was qualitatively measured. The comparisons established a baseline of quality for the radar image simulation model, albeit the comparisons were less direct for PPI than for SLAR. The model produced images which compared extremely favorably with the comparison images. The discrepancies identified fit into the same four general classes enumerated for SLAR. All of the basic comments made for SLAR apply. The point scattering method produced simulated PPI radar images which compared extremely well, within the limitations imposed by a lack of real PPI images for comparison, with the real and simulated SLAR images. It should be pointed out that the reason the simulated PPI images were compared to both the real and simulated SLAR images was to better qualify differences. Had a difference arisen in comparing the simulated PPI to the real SLAR images, it would not have been possible to conclude very much about the PPI simulation model. No such instances were detected. With these images, it was concluded that the simulation model performs exceptionally well. The validation work on the PPI simulation is reported in Section 3.

1.2.3 Summary of Work - Terrain Guidance Applications

The general Point Scattering Radar Image Simulation model was applied to a Terminal Guidance problem. The problem selected was a guidance device which used area correlation between a stored simulated radar image (called a reference scene) and a "live" radar image of the same

scene. The device which produced the area correlation was an electronic "black box" called a Correlatron⁷. The Correlatron used in this work was located at ETL. This meant that reference scenes were formed at RSL, stored on digital magnetic tape, and sent to ETL. There the reference scenes were read from the tapes, formatted properly, and converted into the right reference scene storage medium (35mm film), and input to the Correlatron. Finally, the area correlation test was run. As of this date, final results of this test are pending. Preliminary results indicate very satisfactory operation.

This application of the radar simulation model was important for two basic reasons: (1) The results of the area correlation test would represent a quantitative, not qualitative, measurement of the "goodness" of the Point Scattering Radar Image Simulation Model; (2) It represented the first application which required departure of the model configuration from the "perfect" system model of all previous work. The results would be quantitative in the sense that the determination of quality ("goodness") was to be made by the Correlatron, not by image interpreters or by comparisons to other images made by humans. Up until this application, quality assessments of the images formed by the radar simulation model were all subjective. They relied upon qualitative comparisons to real imagery and appealed to visual assessments of "how good" they were for determination of quality. As of this juncture, at least one quantitative validation of the simulation model has been performed.

The system being modeled for this application consisted of the radar system, the ground scene, the Correlatron, and image (reference scene) storage medium. This task represents the first application of the radar simulation method to model "real-world" processes. Modeling "real-world" processes was necessitated by the nature of the system being

⁷ Klass, Philip J., "Guidance Device Set for Pershing Tests," Aviation, Week and Space Technology, May 12, 1975.

modeled. The Correlatron measures the two-dimensional cross-correlation between the reference scene (simulated radar image) and the real scene. By definition, the cross-correlation is a measure of the degree that one scene is similar to the second (in this application, that is what the cross-correlation measures). This means that the radar simulation configuration needed to model, as closely as possible, the "real-world" processes of the operating system to minimize differences.

Not all operating parameters and characteristics of the real system were known. Only the most important, basic, set of parameters were known. Throughout this work the success criteria built into the Correlatron were unknown by us. The barest of essential information was available to us about the terminal guidance system. This task has largely been one of inferring second-order effects and operating specifications given a few first-order effects and prime parameters. What this means is that the reference scene model implementation developed only departed from the "perfect" system configuration for a limited set of "most important effects. The reference scene software implementation was not developed to be an exact replica of the real system.

The reference scene model developed for this task accounted for the important "real-world" aspects of the radar, ground scene, and Correlatron system. The radar used in this system was a PPI with several unusual operating features: (1) The image scan format was set at a full 360°, instead of the usual 90° sector associated with PPI; (2) The near range angle of incidence was set at 35° and the far range at 65°; (3) The resolution of the radar was purposely set very coarse (the antenna beamwidth was very wide and the pulse was very long) requiring special resolution considerations and averaging; (4) The polarization selected was one for which little empirical data were available; (5) The data were recorded in the ground range mode. These special characteristics were incorporated into the simulation model. All the rest of the radar parameters were chosen as a "perfect" system. These included: (1) The transmitter was assumed to produce "ideal" pulses; (2) The

receiver was assumed to be linear; (3) The antenna pattern was assumed to be "ideal" with no degradations and no sidelobes.

The reference scene format was dictated by special considerations of both the radar system, center and omni-directional approach of the "live" PPI video data with respect to the reference scene, and the Correlatron. These "real-world" considerations were modeled and implemented in the digital computer program developed to form reference scenes. Among these effects were such items as: (1) The reference scene was made larger than the real PPI scene to allow for centering errors; (2) The reference scene was continuous and did not have the "altitude hole" present in the real PPI data; (3) Angles of incidence (radar angle of incidence) in the reference scene were strictly kept in the range⁴ of 35° to 65° regardless of what the actual geometry dictated.

The data base was constructed for a basic resolution much greater than the apparent resolution of the PPI system seemed to warrant. This was done because so little was actually known of the true operating parameters of the PPI. It turns out that this was a wise decision. When first results were produced (these results were photographs, not Correlatron results), an immediate problem was apparent to us. The scene, for simulation purposes, had been degraded to the size of radar resolution cells (determined by antenna beamwidth and pulse length) and these cells were assumed to represent sufficient independent samples of the scene, just as in all previous work. The problem which rapidly manifested itself was that the resolution of the PPI was "coarse" while the previous systems modeled had "medium" resolution. This approach to determine the size of independent samples of the scene, while it works well for "medium" resolution radars (Section 1.4), breaks down for "coarse" resolution radars; it undersamples the scene. Since the basic data base had been constructed for much finer resolution than at first

⁴ The angle of incidence referenced is the angle formed by the local vertical from the antenna to the ground and the "effective" boresight to each resolution cell. This is the angle which was kept in the specified range. Local variations of the slope of the terrain altered this angle to the effective "local angle of incidence," as is normally done.

seemed warranted given the apparent radar resolution, it was possible to modify the reference scene software to simulate the scene at a finer resolution and then to average a specified number of these new, "independent looks." We did not have an antenna pattern for the PPI to incorporate into this change, so a "perfect" pattern was assumed. New reference scenes were produced and photographed. These photographs indicate that, within the limitations imposed by the assumption of a rectangular azimuth and $\csc^2 \beta \cos \beta$ range antenna pattern, the reference scenes are qualitatively correct; they "look" good.

Finally, the backscatter data (σ^0) required to model the "radar return properties" (dielectric properties) of the various "microwave (or radar) categories" identified to be in the test scene and specified in the data base were obtained. These data were obtained from empirical σ^0 data banks⁴ and from the literature. They were not taken from radar images of the test site or of any other, similar, site! Exact matches in the σ^0 data available versus what was required for the frequency and polarization used by the PPI were not always possible. Much effort was expended to produce (obtain) σ^0 data having the backscatter characteristics inferred from the types of scatterers identified to be in the test site and included in the scene. Theory, empirical data, and knowledge and intuition were all brought to bear on the problem. The result of this effort was the set of σ^0 data used to form reference scenes of the test site.

Reference scenes have been produced for the Pickwick Landing Dam test site. These reference scenes have been properly formatted, stored on digital magnetic tape, and these tapes have been sent to ETL for testing on the Correlatron. These test results are pending. Preliminary results indicate very satisfactory performance. The work on this application of the Point Scattering Radar Image Simulation Method is reported in Section 4.

⁴ Bush, T.F. and F.T. Ulaby, "Fading Characteristics of Panchromatic Radar Backscatter from Selected Agricultural Targets," IEEE Trans. Geosci. Electron., Vol. GE-13, October 1976, pp. 149-157.

1.2.4 Construction of Data Bases/Feature Extraction Techniques

The work achieved in the three basic activities performed under this contract required construction of several new data bases. These data bases were built for the topographic area in the states of Alabama, Tennessee, and Mississippi surrounding the Pickwick Dam in Tennessee. Several reasons motivated constructing new data bases. First, existing data bases at RSL were not adequate for the task of validation of the point scattering radar image simulation method. They were neither representative of a significant variety of features and objects which might generally be expected to occur in radar images, nor complex and detailed enough for comparison to real radar images. Second, multiple real radar images of different looks were unavailable for our existing data bases.

It was decided that an adequate validation test could be accomplished by simulating the image products of medium resolution SLAR and PPI radars (resolution cell size approximately sixty feet by sixty feet). Multiple looks of the same site by a real radar were essential for comparison to our simulation results. Since our existing data bases were neither representative of the "average" radar scene nor complex enough nor contained sufficient resolution and, since multiple looks of the scenes of our existing data bases were not available, the decision was made to build a special validation data base. The geographic location of the data base was determined by the support activities of the terminal guidance task (i.e., Section 4).

The terminal guidance task we performed was part of a much larger, over-all, effort. The larger effort had already settled on the Pickwick Landing Dam area as one prime test site. Since it was necessary to construct a data base for this site for one phase of this study, it was decided to use the same site for all phases. The test site contains sufficient topographic and cultural developmental complexity to be appropriate for the validation phase. Also, multiple looks of real imagery were obtained for this area.

Another goal existed for construction of data bases for this study,

evaluation of alternate input data sources and construction time and problems. To accomplish the first part, two versions of a data base were to be built. One version was to be constructed using only optical photographs and topographic maps, the other using only radar images (to determine categories) and topographic maps. The second part of the goal (construction time and problems) was to be accomplished by keeping records and documenting the problems.

Evaluation of the quality of data bases prepared from competing data sources was to be accomplished by comparing the resultant simulated radar images made from them to each other and to real images of the same scene. In general, it was determined that the best data base would be built from a synthesis of radar imagery, optical photographs, and maps. The closer the resolution, operating frequency, and polarization of the source radar imagery to the system being simulated, the better the data base in the sense that data contained in the photographs which would not be necessary for the data base (as indicated by the source imagery) could be eliminated easily. Conversely, regions and boundaries that do not appear on the photographs and maps might appear on the source radar imagery. These could be added as necessary to the data base. Again, it must be stressed that the radar imagery is used only to delineate boundaries and categories, not as a source for greytone.

Bases constructed from optical photography provided the best source material for the principal reason that geometric distortion was minimized. Geometric distortion in radar images presents a real problem which must be treated. When constructing a data base by manual techniques, this problem is severe; with automated techniques and a digital computer, this problem is expected to become more tractable. At any rate, it was concluded that the optical photography was the preferred source material.

The fidelity (both geometric and dielectric) of the ground truth data base is the basis upon which final success is dependent. The final simulated radar image cannot be better than the input ground truth data base; it can only be a degraded version. Constructing data bases for

the necessary fidelity is the biggest single problem facing increased usage of radar image simulation. The term most often applied to this task is feature extraction. Classical techniques for feature extraction are manual techniques. Clearly, a tremendous improvement in the time required to build data bases is needed. Part of this study focused upon the application of interactive processing techniques in constructing data bases. The marriage between computer and interpreter was investigated. The computer is very good at manipulating vast amounts of data in short periods of time and the human is incomparable when drawing upon experience to make decisions. A cooperative approach in which the human is used to make decisions and guide the processing direction of the software, and the computer is used to manipulate the data rapidly and easily and to remove the drudge from the human is desired. Such a system is being designed at RSL. The first phases have been initiated under this contract.

Data bases were constructed and competing sources of input data and feature extraction techniques were evaluated. A study was initiated to evaluate the application of interaction to data base construction. The details of this work are reported in Section 5.

1.3 Summary of Results

Up to now, our radar image simulation work has been concentrated on refinement of the model and efficient software implementations of the real processes being modeled. With the work presented in this report, the transition is made from pure developmental research to validation of the model and to application of it to present problems. With this transition comes the necessity for sophistication in using the model and in applying it to describe realistic systems and "real-world" processes, and the door has opened to a complete new set of problems. These are the problems associated with modeling a complete imaging radar system, with constructing ground truth data bases of real terrestrial scenes, with forming simulated radar images of large scenes containing many data points, with obtaining backscatter data for many different kinds of microwave categories, etc. These problems have been encountered and either solved or worked-around in the work performed under this contract.

This report should form a good baseline of effort for application of radar image simulation (and, in particular, the point scattering radar image simulation model) to present and future problems. The goal of the work reported in this document has been to test and validate the point scattering simulation method by direct applications of the model to specific scenes and comparison of the results with real imagery of the same scene. The results of these tests and validation tasks have shown the superior nature of the point scattering radar image simulation model. The simulations produced clearly show that our model and our radar simulation approach produce results beyond the state of the art. In fact, as of this juncture, radar image simulation is no longer an art, it is a science, an engineering tool, a tool to be used.

The point scattering radar image simulation model has been tested in three different applications: (1) Validation of a SLAR model by comparison of simulated imagery to real SLAR imagery of the same scene; (2) Validation of a PPI model by comparison of simulated PPI imagery to simulated and real SLAR imagery of the same scene (done because real PPI imagery of the validation site were not available); (3) Quantitative

testing of the application of a PPI model to a terminal guidance problem using the Correlatron⁷. Superior performance of our radar simulation model has been reported in each phase of these tasks. In addition to these tests of our model, data base construction and feature extraction tasks and studies have been conducted. Clearly, the data base construction work was accurate, as attested by the simulation results. From this work and our knowledge of radar image simulation, a philosophical concept for an interactive feature extraction system is discussed. A brief summary of the results produced, the work performed, and the philosophy developed follows.

1.3.1 Summary of Results - SLAR Validation

An assessment of the composite of tasks involved in simulating Side-Looking Airborne Radar (SLAR) images has been accomplished through comparison of simulated images with Goodyear APD-10 Synthetic Aperture Radar Imagery. The geometric fidelity, textural consistency, and relative graytone accuracy of the simulated images have been shown to be excellent. The implication of the results is that not only are the Point Scattering Model and its software implementation verified, but also the ground truth data base and its associated elevation and backscatter content faithfully represent a discrete sampling of the Pickwick site.

The capabilities developed as by-products of the validation tasks may be extended in their usefulness. There may be applications in the areas of ground truth data base construction, scene modeling, image handling, and backscatter data acquisition to which these capabilities may be well suited.

There are potentially many present and future problems in which radar image simulation in general, and our model and approach, in particular, should be used. Without knowing the details of any of these potential applications we can infer from our research to date some problem areas in need of development if radar simulation is, in fact, to be used. This validation of our model has had a prime goal of testing the model, but a by-product of this work has been to show the utility and versatility of our model and its potential range of

⁷ Klass, Philip J., "Guidance Device Set for Pershing Tests," Aviation Week and Space Technology, May 12, 1975.

applications, and, as a result of performing the work, has identified the kinds of problem areas we expect to be encountered in future radar image simulation applications. These serendipitous results should not be ignored. They should be implemented and additional research into these problem areas should be initiated. Many of these studies are discussed in Section (7.).

1.3.2 Summary of Results - PPI Validation

The geometric fidelity, textural consistency, and relative grey-tone accuracy of simulated Plan-Position Indicator (PPI) images have been validated by comparison to both simulated and real SLAR imagery of the same scene. Validation of the PPI simulations by comparison with SLAR imagery was forced by the unavailability of real PPI imagery of the same scene. The simulated PPI radar parameters were established to produce terrain radar images in the PPI scan format but with the gain and bias set to match SLAR image quality. Most of the comments made about the SLAR validation in Section (1.3.1) apply here, to the PPI validation.

In addition, the PPI model was used to make reference scenes, so all the comments about quantitative validation of the model made in Section (1.3.3) apply here. This fact demonstrably improves the quality of the validation performed for the PPI model.

1.3.3 Summary of Results - Reference Scene Simulation

Five reference scenes have been produced of the Pickwick Landing Dam Test Site. These reference scenes have been properly formatted, stored on digital magnetic tape, and these tapes have been shipped to ETL for testing on the Correlatron. The complete test results are not yet available; however, preliminary results are very satisfactory. The preliminary results indicate that in this test application (production of reference scenes for terminal guidance) our radar image simulation model meets, or exceeds the success criteria. The success criteria developed for this test are, at least, threefold: (1) Degree of cross correlation between our reference scene and the "live" PPI data greater than some threshold; (2) Difference between cross correlation peak and the "known" center of the "live" data less than some maximum

value ("centering" error); (3) Repeatability of results. We do not know the exact criteria values that were used by ETL. We do know, however, that preliminary results indicate that we meet or exceed these criteria.

The first criterion, degree of cross correlation, is important to the validation of our simulation model. Since preliminary results show that our reference scenes meet the criteria, even without having the details of the test results for presentation here, we can infer that the degree of cross correlation between our reference scene and the "live" PPI data of the same scene always exceeds the threshold (repeatability infers "always"). This is an important result. It means that our reference scene of the test site is very much like the real PPI image of that site. This claim is further substantiated by knowledge that the "centering" error between our simulated image and the real image is equal to or less than the criterion. These three measurements, degree of cross correlation, location of the correlation peak, and repeatability, together represent a first quantitative validation of our model. This quantitative validation coupled with the subjective validations reported earlier (1.3.1 and 1.3.2) combine to demonstrate that not only is our model a superior one, but it is available and can be applied to solve present and future problems.

This is emphasized by the nature of the task summarized here. The task is a real, present problem. The problem, of course, is to use radar image simulation to produce reference scenes for guidance applications. This problem has been researched for some time now, but results haven't been repeatable. Our radar image simulation model was applied to this problem and the results indicate success has been achieved. We wish to interject a note of caution at this point. Our results have been produced only for a limited set of conditions: One test site, one altitude, one radar system model. More conditions need to be tested before it can be claimed that the problem is solved. In fact, our model lends itself exceptionally well to these kinds of studies. Now that we have achieved preliminary success, the virtues of our simulation model should be utilized (ease of parameter change to test step-wise degradations, etc.) and it should be applied to many

studies about this concept of guidance and the particular hardware involved. Doing this would maximize the information return for the resources invested and would also produce quantitative answers to questions which are presently a puzzle.

1.3.4 Summary of Results - Data Base Construction/Feature Extraction

The work performed in the three basic simulation activities performed under this contract required construction of two new data bases. These data bases were built for the topographic area in the states of Alabama, Tennessee, and Mississippi surrounding the Pickwick Dam in Tennessee. These data bases were built using high resolution aerial photographs and maps as the input source intelligence information and were built using manual feature extraction techniques. The simulation results produced attest to the quality of the data bases built. This is not to say that better data bases couldn't be built, for they certainly could. It is to say, however, that our analysis of the level of detail to include in the data bases, our feature extraction techniques, and the data bases produced served admirably the purposes for which they were built.

A study was performed to evaluate data bases constructed from alternate kinds of source intelligence data. Two data bases were constructed during this study. One using optical photographs and the other using radar images as the source intelligence data for feature extraction. (Note: At no time during the contract has radar imagery been used as a source for either σ^0 data or greytone data for input to any of our simulations even though they were used as source intelligence data for constructing data bases). Construction time was recorded for both data bases. It was found that construction time did not vary appreciably as a consequence of using the two different intelligence data sources. It has been concluded, however, that the "best" data base could be constructed if many sources of intelligence data (i.e., maps, high-resolution aerial photos, radar imagery, infra-red imagery, etc.) were available. If limited to either optical products or radar products, though, we concluded the geometrical distortion problem inherent in radar imagery decides the question in favor of optical products.

As a natural consequence of performing this work, the study of feature extraction techniques we performed has led us to conclude that construction time and, perhaps, final quality of data bases for radar image simulation can be improved by use of interactive techniques. A simplistic interactive feature extraction concept has been developed and is reported in Section 5. As we visualize it, interactive feature extraction means combining the photo-interpreter and computer into a workable, real-time data base construction 'team'. The value of this team can be brought into natural focus by development of an interactive processing station devoted solely to this task. The results produced under this contract indicate that radar image simulation has become a science and is ready for application to many different problems. To support the potential proliferation of radar image simulation applications, serious consideration needs to be given to the problem of constructing data bases. We think that an interactive feature extraction approach is optimal.

1.4 Qualifications, Limitations, and Constraints of Model

The point scattering radar image simulation model rigorously treats properties of the radar system, ground scene, and image medium. The relationships and interrelationships between these various aspects of a radar image are rigorously modeled and mathematically expressed. The model, as developed and reported by Holtzman, et al.^{1,2}, is completely general and complete. The model, in this form, properly simulates medium to coarse resolution SLAR's (Side-Looking Airborne Radars) and PPI's (Plan-Position Indicators) depending upon the details of the software implementation of the model. Implicit in all of our previous work, whether or not explicitly stated, was the fact that the systems being modeled were "ideal". The radar system was ideal as was the ground scene and, the image. All radar system parameters, for simulation purposes, were assumed to be "ideal". The radar system had a "perfect" antenna pattern (no sidelobes and no distortions), the transmitter produced "perfect" pulses, and the receiver was linear. The ground was modeled as a collection of "perfect" homogeneous regions (distributed targets) which reradiated energy described exactly by empirical differential cross-section data (σ^0) plus ideal (isotropic) specular reflectors (cultural targets) which were treated symbolically. The image (film) was modeled as linear ($\gamma = 1$) over its entire dynamic range with "perfect" exposure and development and with compression neither at low nor high densities. All of these ideal assumptions, and more, have been necessary in all previous work. They were necessitated not by the model, but instead, by the simulation software implementation of the model. That is, they were forced for computational efficiency and, since up to now it has not been necessary to model a "real" system; an ideal system was as good as any other (and more efficient for computational purposes) for modeling. Up to now, the radar image simulation work has concentrated on refinement of

¹ Holtzman, J. C., V. H. Kaupp, R. L. Martin, E. E. Komp, and V. S. Frost, "Radar Image Simulation Project: Development of a General Simulation Model and an Interactive Simulation Model, and Sample Results," TR 234-13, Remote Sensing Laboratory, The University of Kansas, Feb., 1976.

² Holtzman, J. C., V. H. Kaupp, and J. L. Abbott, "Radar Image Simulation Project," TR 234-15, Remote Sensing Laboratory, The University of Kansas, September, 1976.

the model and efficient (and correct) software implementations which were representative of the ideal processes being modeled. An operational system on the other hand will require specialization, some of which will require more detail, some less, to produce an overall cost-effective implementation.

With the work presented in this report, radar image simulation makes the transition from infancy to a first stage of maturity. In this work the model, software implementation, ground truth data base concept, use of empirical differential cross-section data, etc., are validated through comparisons to real radar imagery of the same site and look-direction. This work is reported in Sections 2. and 3. for SLAR and PPI models, respectively. In these sections, the software are set-up to model medium resolution radar systems. All the necessary assumptions of the basic model are satisfied. "Perfect" system models are justified. In Section 4., another step is taken. The point scattering radar image simulation method is structured to accurately model "real-world" processes where such modeling is made necessary because the system being modeled (radar, ground scene, and Correlatron) eliminates some of the generality of the basic simulation model. Changes therefore are required to represent accurately the system configuration being simulated. The important point to be stressed is that the point scattering simulation model is general and rigorous, and has a number of basic premises upon which it rests. Insofar as these premises are explicitly satisfied by the radar system being modeled, minimum changes are required in the software implementation of the model as changes of radars being modeled occur, just as in the work reported in Sections 2. and 3. When these premises are not all explicitly satisfied, as in the work reported in Section 4., then the software implementation of the basic model is altered to account for the variations and degradations from the ideal system.

In order to evaluate the work and results presented in this report, the basic assumptions, limitations, and constraints upon which the general point scattering radar image simulation model rests are enumerated and discussed.

An appropriate starting point for this discussion is the final computational algorithm (equation) of the Point Scattering Method. After the ground truth data base (terrain feature model) of the site to be simulated has been specified, the reflectivity (σ^0) data for the various categories included in the data base have been obtained, and the complex geometry relating the radar platform to the scene has been determined, the greytone equation is used to calculate the power reradiated from the ground back to the radar for each pixel (picture element) in the image. It calculates the intensity of the ground-return signal exiting the receiver, and the conversion of this intensity into the appropriate density of silver grains in the exposed and developed image. This algorithm determines the shade of grey of each pixel in the image, and hence, is called the greytone equation. The greytone equation produces the final result, drawing upon all preceding data and calculations. It relates the ground to the radar and to the image. The greytone equation predicts the power reradiated from each resolvable ground element (resolution cell). The size of a resolution cell is determined in the range direction by the pulse length and in the azimuth direction by the directional properties of the antenna. For the purposes of radar image simulation, let us assume that the ground can be modeled as a collection of homogeneous regions each at least the size of a resolution cell (i.e., distributed targets). The power reradiated from all the scattering centers located within a resolution cell combine at the receiving antenna to produce one value for the resolution cell and we designate it the return power (P_R).

In reality the return power is not a deterministic process as this might imply. The amplitude of the return power received by the antenna mounted on a moving vehicle fluctuates widely because of variations in the phase of the reradiation from the different scatterers in the illuminated area (resolution cell). This phenomenon accounts for the speckled nature ("grainy" appearance) of radar images and is called "fading." The statistics of a "fading" signal have been well-documented for most

homogeneous targets and it has been shown that the signal amplitude can be described by a Rayleigh⁴ probability distribution⁵.

If we assume square-law detection in the radar being modeled, then the postdetection signal is a random variable having a chi-square probability density function with $2NS$ degrees of freedom⁴ where NS specifies the number of "Independent samples" being averaged. The minimum width of a backscatter lobe in the azimuth direction is specified as $L/2$ where L is the antenna length. A real-aperture SLAR (Side-Looking Airborne Radar) has an azimuth resolution given by BR where B is the diffraction-limited beamwidth given by λ/L (the illuminating energy wavelength divided by the antenna length L) and R is the range distance from the antenna to the resolution cell on the ground. From these two concepts of resolution we can determine the number of "Independent samples" which are effectively combined to produce the instantaneous average return power (P_R) from a resolution cell:

$$N = \frac{BR}{L/2} = \frac{2R\lambda}{L^2} \quad (1)$$

In a fully-focused synthetic-aperture radar the synthetic azimuth beamwidth is $L/2$, so there is but one sample of the random process ($NS = 1$) used and, hence a grainier appearance in the radar image.

⁴The Rayleigh probability distribution is just one of several feasible probability models which can be used to describe the signal amplitude variation [8,9]. Use of a different probability model would modify the resulting "fading" per cell somewhat. However, for medium to coarse resolution radars, final averaging yields similar results.

⁵Reeves, R.G., A. Anson, and David Landen, Manual of Remote Sensing, Vol. 1, Chapter 9, American Society of Photogrammetry, Falls Church, Va.

⁴Bush, T. F. and F. T. Ulaby, "Fading Characteristics of Panchromatic Radar Backscatter from Selected Agricultural Targets," IEEE Trans. Geosci. Electron., Vol. GE-13, October 1976, pp. 149-157.

Averaging a larger number of "independent samples" reduces signal fading and, thus, smooths the image appearance⁸. But, increasing the number of samples averaged also degrades the final image resolution.

After detection, it can be shown that the return power from each resolution cell is estimated by⁹

$$P_R = \left(\frac{\bar{P}_R}{2NS} \right) (Y) \quad (2)$$

where \bar{P}_R is the expected value of the return power from a resolution cell, Y is a random variable with a standard chi-square distribution having $2NS$ degrees of freedom, and NS is the number of "independent samples" averaged (Equation 1). When the number of independent samples being averaged is large, (2) becomes (3)

$$P_R = \bar{P}_R \left(1 + \frac{RN}{\sqrt{NS}} \right) \quad (3)$$

where RN is a normalized Gaussian random variable with zero mean and unit variance.

For terrain that can be modeled as a collection of homogeneous, distributed, targets the value of P_R calculated from either (2) or (3) is the best estimate of return power after detection that can be made when each resolution cell is treated as a single point. If the terrain cannot be modeled in this way the location and reradiation properties of each of the numerous scattering points within a resolution cell are modeled, the amplitude and phase of the return from each point is calculated, and the resulting phasor sum at the antenna (magnitude) is chosen to become the estimate of return power. For high-resolution and synthetic aperture radar applications of radar image simulation, either approach is possible but the latter is computationally inefficient and requires investment of a vast amount of time to properly model the ground. For medium resolution

⁸ Porcello, J. L., Norman G. Massey, Richard B. Innes, and James M. Marks, "Speckle Reduction in Synthetic - Aperture Radars," J. Opt. Soc. Am., Vol. 66, No. 11, November 1976.

⁹ Frost, V.S., J.L. Abbott, V.H. Kaupp, J.C. Holtzman, "Derivation of the General Fading Characteristics for Radar Image Synthesis and Analysis," TR 319-29, Remote Sensing Laboratory, The University of Kansas, Sept., 1977.

applications such as those reported here, Equations (2) and (3) represent very good estimates of the post-detection return power.

Usually after detection the intensity of the video signal exiting the receiver is recorded on film. This can be expressed by [4]

$$D = \gamma \log_{10} P_R + \gamma \log_{10} M + \log_{10} K \quad (4)$$

where P_R is given by either Equation (2) or (3); D is the density of metallic silver grains in the exposed transparency corresponding to the intensity of the illumination; K is a constant depending upon the exposure time and the film processing and development time; γ is a positive constant representing the slope of the linear portion of the film curve of density versus logarithm of exposure (the Hurter-Driffield curve³) where $\log_{10} K$ is the extrapolated intercept of this line; M is the transfer function of the radar receiver (including all appropriate linear and non-linear effects such as AGC, Automatic Gain Control, or saturation) such that the video intensity incident on the film during exposure is specified by MP_R .

When implemented on a digital computer, the simulation process must be quantified. The return power calculated for each resolution cell is coded into one pixel in the simulated image. Each pixel in the image will represent one precise shade of grey between black (no return power) and white (saturated signal, high return power). Thus, Equation (4) for the film density must be altered to reflect digital data processing requirements. The shade of grey (greystone) for each pixel in an image can be shown to be specified by $G_R = \left(\frac{2^N - 1}{g}\right) D$ where D is given by Equation (4), 2^N is the number of discrete levels of grey available in a computer word having N bits, and g is the base 10 logarithm of the dynamic range of the radar signal being mapped into the linear portion of the film dynamic range. The general Point Scattering Method radar image simulation model, as given earlier and reported by Holtzman, et al.¹, uses this result

³ Goodman, J. W., "Introduction to Fourier Optics," McGraw-Hill, Inc. 1968.

¹ Holtzman, J. C., V. H. Kaupp, R. L. Martin, E. E. Komp, and V. S. Frost, "Radar Image Simulation Project: Development of a General Simulation Model and Interactive Simulation Model, and Sample Results," TR 234-13, Remote Sensing Laboratory, The University of Kansas, February, 1976.

to describe imaging radar mathematically. The complete derivation of the greytone equation has been reported previously¹ and so the result will not be repeated here. As previously reported and using the result for image density, the greytone equation can be seen to be given by:

$$G_R = G_{R_c} + \frac{2^{N-1}}{g} \left\{ \gamma \log_{10} \left[\frac{P_{T_c} \sigma_c^0(\theta_{\ell}) A G_c^2(\epsilon_c) \lambda^2 R_c^4}{P_{T_c} \sigma_{a_c}^0(\theta_{\ell_c}) A_c G_c^2(\epsilon_c) \lambda^2 R_c^4} \right] + \log_{10} \left(\frac{k}{k_c} \right) + \gamma \log_{10} \left(\frac{M_c}{M_c} \right) + \gamma \log_{10} \left(1 + \frac{RN}{\sqrt{Ns}} \right) \right\} \quad (5)$$

where:

- G_R = The instantaneous greytone, including fading, to be calculated for each pixel in an image;
- G_{R_c} = The calibration greytone value added to the value computed for each pixel to calibrate the image according to a known calibration point;
- γ = A property of the image medium (in this case, film, i.e. image medium transfer function);
- P_T = The transmitter output power of the radar being simulated;
- P_{T_c} = The transmitter output power of the calibrator;
- $\sigma_c^0(\theta_{\ell})$ = The scattering coefficient for each ground point;
- $\sigma_{a_c}^0(\theta_{\ell_c})$ = The scattering coefficient for the calibration point;
- A = Area of the ground spot resolution cell illuminated for each pixel by the radar being simulated;

¹ Holtzman, J. C., V. H. Kaupp, R. L. Martin, E. E. Komp, and V. S. Frost, "Radar Image Simulation Project: Development of a General Simulation Model and an Interactive Simulation Model, and Sample Results," TR 234-13, Remote Sensing Laboratory, The University of Kansas, Feb., 1976.

⁵ Reeves, R. G., A. Anson, and David Landen, Manual of Remote Sensing, Vol. 1, Chapter 9, American Society of Photogrammetry, Falls Church, Va.

- A_c = Area of the ground spot resolution cell illuminated by the calibrator;
- G = One-way gain of the antenna of the radar being simulated (in the direction of A);
- G_c = One-way gain of the antenna of the radar being simulated (in the direction of A_c);
- N = The number of bits assigned to each image pixel for greytone (i.e., the computer word length used);
- g = The \log_{10} of the ratio of a bright return to a dark return (i.e., simulated radar gain - one-to-one mapping of radar signal onto film occurs when $g = 2$);
- λ = Wavelength of the electromagnetic energy transmitted by the radar being simulated;
- λ_c = Wavelength of the electromagnetic energy transmitted by the calibrator;
- R = The distance from the antenna of the radar being simulated to each ground resolution cell (pixel);
- R_c = The distance from the antenna of the calibration system to the reference ground spot;
- k, k_c = Constants which depend upon the exposure time and on the film processing and development;
- M, M_c = Constants of proportionality relating the return electromagnetic power received by the antenna to intensity on the film;
- N_s = The number of independent samples contained in uncorrelated resolution cells;
- RN = A Gaussian distributed random number with zero mean and unit variance.

where substitution for D and P_r has occurred and the result has been calibrated. Calibration is shown in two phases. The first phase of calibration is accomplished by calculating the photographic density of a point in the image. This is accomplished via the parameters subscripted "c" ("c" stands for calibration) and by selecting a value for g . The

second phase is setting G_R , the greytone of that point, to a desired level (between 0 and 2^{N-1})^c. Together these calibration parameters have the effect of determining how much of the dynamic range of the radar signal will be mapped into the 17-20 dB dynamic range available in ordinary film, and exactly what portion of the dynamic range of the radar signal will be displayed.

In the development leading to Equation (5), the power reradiated as a result of the illuminating-energy/terrain interaction was not specified. An excellent model for the return power reradiated from distributed targets is given by the radar equation⁵

$$\bar{P}_R = \frac{P_T G^2 \lambda^2 \sigma^0 A}{(4\pi)^3 R^4} \quad (6)$$

where the average transmitted power is represented by P_T ; the two-way gain of the transmitting/receiving antenna (a function of the elevation, and azimuth angles) is given by G^2 ; the transmitted wavelength is given by λ ; the reflectivity model, (a function of wavelength and local angle of incidence, among others) is σ^0 ; the element of area on the ground being sensed (a function of the ground slope, pulse length, antenna beamwidth, and altitude) is A ; and the range from the antenna to the element of area being sensed is R .

Certain conditions must exist for this form of the radar equation to be valid. First, the area being sensed must be a distributed target. A distributed target is a homogeneous region of a specific radar reflectivity category in which there must be a large number of individual scattering centers located within a resolution cell and they must be positioned randomly [4]. Second, it must be assumed that all the parameters of the radar equation are constant across a resolution cell. When these conditions are satisfied by both the terrain being simulated and radar being modeled, then Equation (6) a particularly tractable form of the radar equation, can be used in the greytone Equation (5) in conjunction with either Equation (2) or (3) to estimate the return power from each resolution cell.

Implicit in equation (5) are all the normal radar effects such as

layover, shadow, range compression, etc. These and similar effects depend only on the specific implementation of the model. That is, the software realization of the point scattering simulation model must include specific provisions to account explicitly for these effects. The responsibility for precision of treatment of these effects rests solely with the specific software implementation of the model.

Also implicit in equation (5) are a number of assumptions upon which the model rests. These assumptions are basic to the model and cannot necessarily be eliminated through software by careful implementation of the model although their impacts can definitely be minimized. These assumptions are discussed in the following sections.

Just as all mathematical models are abstractions of reality, so is the point scattering radar image simulation model. The point scattering simulation model attempts to describe, in closed form, the "real-world" processes of the radar imaging system as a closed system consisting of ground scene, radar processor, and image medium. As just noted, this model rests on some basic premises. These premises may be viewed both as the necessary assumptions to make the model work, and as the limitations and constraints of the model. Depending upon the applications for which the model is intended to be used, these limitations and constraints may be of no significance or they may be of critical importance. It is important that these limitations be recognized and accounted for in order to insure that the model is appropriate for a specific task. For the general model, the more important of these premises can be succinctly stated as:

- (1) Validity of the radar equation for simulation;
- (2) Validity of using empirical differential scattering cross-section (backscatter) data (σ^0) to model the electromagnetic properties of the ground (ground return data);
- (3) Validity of the ground model (data base) concept;
- (4) Validity of the radar receiver model;
- (5) Validity of the image medium model;

The impact each of these premises has for simulation is discussed in the next sections. In particular, the premises are defined and how they affect

simulation is explained. The ultimate test of any model once implemented is the correlation of its results with real world events. As can be seen by reference to the later sections of this report, the results produced by the Point Scattering Method are very good. Thus, practical treatment of these limitations and constraints is shown to be valid by appeal to the results produced.

1.4.1 Validity of the Radar Equation for Simulation

1.4.1.1 Return Power Model

The greytone equation (5) has been developed to be specifically applicable to distributed targets. Recall that a distributed target is a homogeneous region of a specific microwave scattering category. This homogeneous region must be at least as large as the resolution element of the radar being modeled, the individual scattering centers located in a resolution cell must be positioned randomly, and there must be a large number of them. With these qualifications about distributed targets, an average value of the scattering cross-section can be used (instead of the actual scattering cross-section associated with each scattering element) and it can be assumed that all the parameters of the closed system model are essentially unchanged from one part of the resolution cell to another. When this is true, the radar equation assumes the following particularly tractable form⁵ in the point scattering model:

$$\bar{P}_r = \frac{P_T G^2 \lambda^2 \sigma^0 A}{(4\pi)^3 R^4} \quad (7)$$

where: \bar{P}_r = Average power returned measured at the antenna terminals;

P_T = Average power transmitted;

⁵Reeves, R. G., A. Anson, and David Landen, Manual of Remote Sensing, Vol. 1, Chapter 9, American Society of Photogrammetry, Falls Church, Va.

- G = Gain of the antenna (assumed to be equal for both transmission and reception) in the direction of the target;
 R = Distance from the antenna to the target;
 σ^0 = Effective differential scattering cross-section of the distributed target;
 λ = Carrier wavelength of the transmitter.

The notions of homogeneity of distributed targets and their size compared to a resolution cell are very important. If these constraints are not satisfied for certain applications, the simplifications resulting in Equation (7) may render the point scattering simulation method using Equation (5) invalid for those applications. If the cell is assumed to contain only a few scattering centers and phase can be ignored, the radar equation has the following form⁵:

$$\bar{P}_r = \frac{\lambda^2}{(4\pi)^3} \sum_{i=1}^N \frac{P_T G_i^2 \sigma_i}{R_i^4} \quad (8)$$

- where: (1) The summation is over the N scattering centers located within the resolution cell;
- (2) The subscript i illustrates that the power transmitted, antenna gain, and distance will be different for each of the scatterers;
- (3) σ_i is the scattering cross-section for each of the scattering centers located within the resolution cell.

If the resolution cell is assumed to contain a large number of scatterers but the radar parameters vary across the resolution cell, the summation can be replaced by an integral using an average value of the scattering cross-section per unit area and then integrating over the area of the resolution cell⁵:

$$\bar{P}_r = \int_{\text{Scattering Area}} \frac{P_T G^2 \lambda^2 \sigma^0(A) dA}{(4\pi)^3 R^4} \quad (9)$$

⁵ Reeves, R. G., A. Anson, and David Landen, Manual of Remote Sensing, Vol. 1, Chapter 9, American Society of Photogrammetry, Falls Church, Va.

where: dA = A differential element of ground area.

Equation (7) represents a special case of (9). An additional assumption is made that all of the parameters in (9) are unchanged across the resolution cell. When this is true, the integral in (9) can be replaced by the product of the factors and this simplifies directly to Equation (7) which is used whenever possible in the point scattering simulation model, Equation (5).

Thus, it has been shown that the point scattering radar image simulation model using equation (7) to calculate the return power in the grey-tone equation (5) rests squarely upon the requirements of the concept of resolution cell, the number of scattering centers and their distribution within the resolution cell, the validity of using an average value differential scattering cross-section instead of the cross-section of individual scatterers, and constancy of the parameters across the resolution cell. If these conditions are not met, the basic model must be changed to incorporate either Equation (8) or (9), whichever is appropriate. This change would have a dramatic impact upon the computational efficiency of the resulting computer programs, but it would provide for simulation of scenes which would otherwise be impossible. It should be noted that the assumptions resulting in Equation (7) are almost never exact, but the approximations are generally good enough. In fact, experience has shown the approximation to be good enough over a considerable range of different radar resolutions and microwave categories.

1.4.1.2 Resolution Cell Size

Figure 2 illustrates the geometry for a pulse radar for which Equation (7) is valid. Reference to Figure 2 will show the concept of resolution cells. The resolution cell is the area on the ground defined by the range resolving capability of the radar in the y-direction (range direction) multiplied times the half-power beam width of the antenna beam (real or synthetic) in the x-direction (azimuth direction). In a real aperture system image resolution in the azimuth direction (x-direction), ω , is essentially determined by the angular width β_h , of the antenna beam.

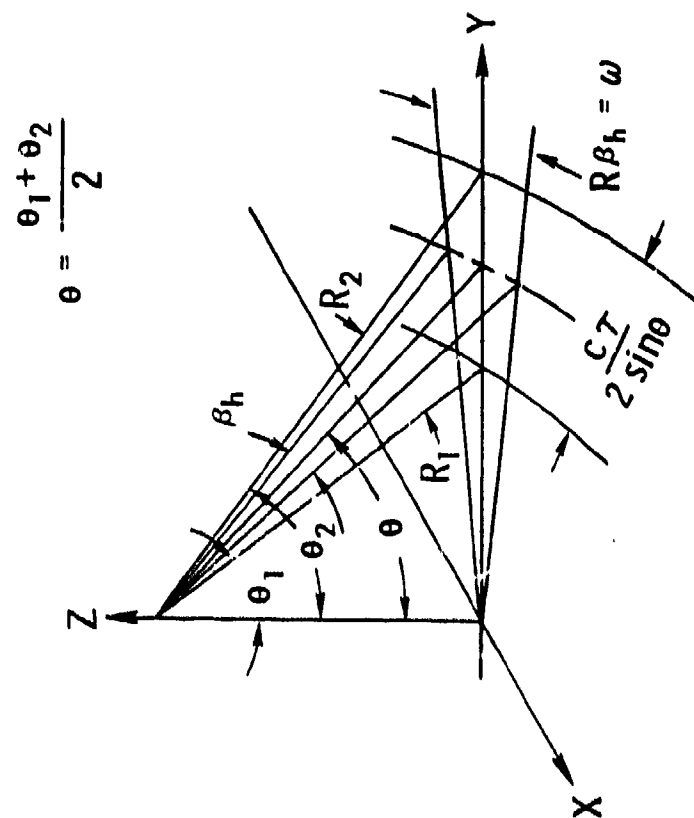


Figure 2. Flat Earth Geometry

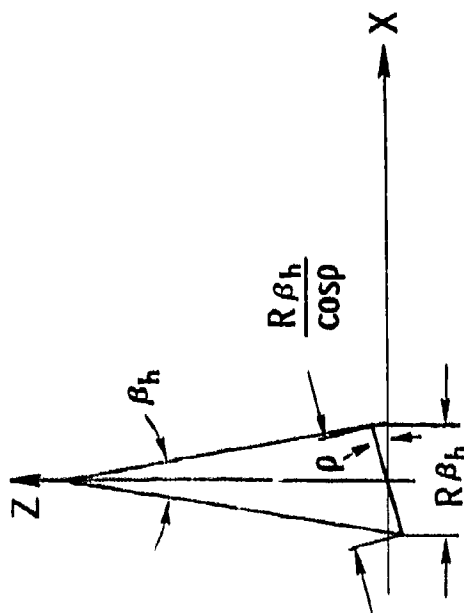


Figure 3. Azimuth Geometry - Slope

A diffraction-limited antenna has a far-field angular half-power beam-width of

$$\beta_h \approx \frac{\lambda}{D} \quad (\text{Radians}) \quad (10)$$

where: λ = Illuminating wavelength;

D = Antenna length.

Provided that $\beta_h \ll 1$ radian, this expression (10) can be used to define the width of the (level) ground in the azimuth direction of the antenna:

$$\omega \approx R\beta_h \quad (11)$$

where: R = Distance from the antenna to the target.

This distance is depicted in Figure 2. Ground slope in the azimuth direction is shown in Figure 3. Figure 3 is a two-dimensional plot of only the xz-plane showing ground slope in the azimuth direction (ρ) added to the simple geometry depicted in 2. As can be seen by reference to Figure 3, if it is assumed that the beamwidth doesn't narrow appreciably on one side and expand appreciably on the other, then the ground distance of the resolution cell in the azimuth direction (when ground slope in the azimuth direction is present) can be specified simply as

$$\omega \approx \frac{R\beta_h}{\cos \rho} \quad (12)$$

Image resolution on the ground in the range direction (y-direction), ℓ , can be shown to be approximately:

$$\ell \approx \frac{c\tau}{2\sin \theta} \quad (13)$$

where: c = Speed of light;

θ = Angle of incidence between antenna and local vertical;

τ = Pulse length in a short-pulse radar system.

This distance is also shown in Figure 2, but it can be seen best by reference to Figure 4.

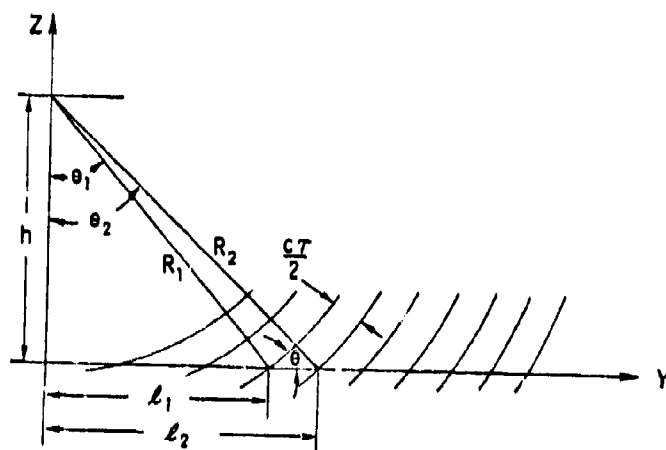


Figure 4. Pulse-Length Resolution

If the assumption is made that R_1 and R_2 are essentially parallel, then $\theta_1 \approx \theta_2 = \theta$ and it can be seen that:

$$l = l_2 - l_1 \approx \frac{c\tau}{2\sin\theta} \quad (14)$$

where it should be obvious that the higher the altitude, the shorter the pulse length, and the larger the angle of incidence (θ), the better this approximation is. Ground slope in the range-direction is shown in Figure 5. This figure is a plot of only the yz-plane showing ground slope in the range direction (δ) added to the simple geometry of Figures 2 and 4. Reference to Figure 5 will show that the ground distance in the range direction of a resolution cell is given by

$$l = \frac{c\tau}{2\sin(\theta - \delta)} \quad (15)$$

Reference back to Figure 2 will show that the area (A) of the radar resolution element is approximated by

$$A = l\omega$$

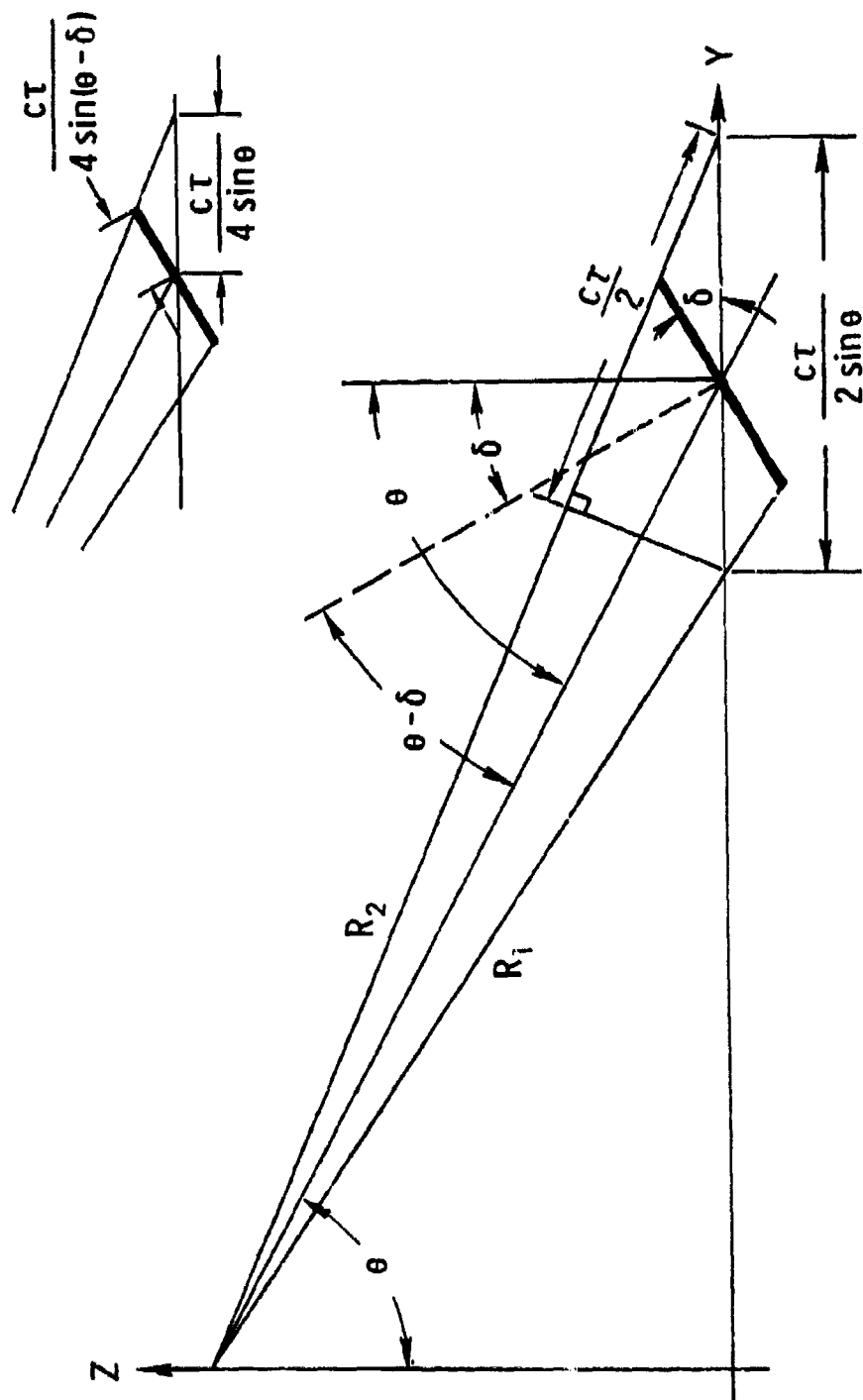


Figure 5. Range Geometry - Slope

or, substituting

$$A = \left(\frac{R^2 h}{\cos \theta} \right) \left(\frac{c^2}{2 \sin(\theta + \delta)} \right) \quad (16)$$

where: ℓ = Length of the resolution cell in the range dimension
(Equation (15));

ω = Width of the resolution cell in the azimuth direction
(Equation (12)).

This result (16) is computationally efficient and is used in applications of the point scattering simulation method developed to date. Alternative expressions for the resolution cell area can be developed including expressions which are exact. However, the computational efficiency of such expressions is typically very much worse than that possible through the use of Equation (16). In a fully focused synthetic aperture system, the resolution in the azimuth direction is given for a flat earth model by $D/2$ where D is the physical antenna length. Since the application of this model was intended for only a medium to coarse resolution system, the synthetic aperture system would logically be incoherently averaged to reduce the image speckle. That is, if one is modeling a 60 foot system, either a 120 foot antenna is used (hardly likely) giving one independent sample per cell or a much smaller antenna is used and degraded to the appropriate final resolution. Since film is the final image medium and is equivalent to square law detection, the incoherent averaging to a resolution ω is equivalent to a real aperture system of that same resolution with $\frac{2\omega}{D}$ independent samples averaged. This is essentially what is done in the point scattering model in the final greytone computation.

1.4.1.3 Resolution Cell Size: Alternate Method

The preceding method for determining the size of a radar resolution cell is computationally efficient but is a good estimator of the resolution cell size only for simulating narrow beamwidth, short pulse length radars over fairly even terrain. It requires a one-to-one correspondence between radar resolution cells and ground truth data base points. This is

accomplished by sampling the terrain reflectivity data once per resolution cell. Sample spacing comes from modeling the ground as if the earth were flat in the region of interest. Then the relative elevation variations contained in the data base are used to correct the size of this "flat-earth" radar resolution cell via equation (16) for determining the area contributing to the return power, and to determine the local angle of incidence for determining the value of backscatter (σ^0 - differential scattering cross-section) used for this.

An alternate method which is more accurate for determining the size of a resolution cell from a digital ground truth data base (called data base) has been developed. This approach requires that the data base represent sampling of the terrain reflectivity categories and elevation variations on a finer scale than the radar resolution cell. A good minimum ratio for data base points to resolution cells is five (5) in both the range and azimuth directions. When this is satisfied, then the following method can be invoked for determining exactly which data base points contribute to the return power from each radar resolution cell, what backscatter categories are physically present within the resolution cell thereby allowing simulation of multiple categories per resolution cell, and for determining such parameters as range, size of the cell, local angle of incidence, shadow, layover, etc.

Assume it is desired to simulate the images produced by a narrow beamwidth, short-pulse radar. This is not a restriction, it merely allows us to specify the resolution element of one kind of radar in the range direction by $\frac{c\tau}{2}$ where τ is the pulse length and c is the speed of light, and in the azimuth direction by $\beta_h R$ the half-power antenna beamwidth (β_h) multiplied times the range (R) to each resolution cell. Assume also that the data base represents much finer sampling of the terrain than the radar resolution cell and that each point in the data base consists of the four-tuple of range and azimuth location, elevation, and backscatter category (x, y, z, c), respectively. For computational simplicity, further assume that the size of the resolution cell can be modeled as though it's independent in both range and azimuth directions. This is not exact, but is

a reasonable approximation.

Figure 6 shows the typical geometry in the range direction for a short - pulse radar system. For such systems the range resolution is specified by $\frac{CT}{2}$. Figure 6 shows a terrain profile with arcs of equal range increments of $\frac{CT}{2}$ superimposed on it. The first return signal it is desired to process is that one labeled R_0 and the last is labeled R_N . Each succeeding arc is farther from the origin than the preceding by $\frac{CT}{2}$ (eg., $R_6 = R_5 + \frac{CT}{2}$). The ground distance between consecutive arcs represents the length on the ground of the resolution cell in the range-direction or, alternatively, the separation between the arcs specifies which (and how many) data base points lie in the increment. The ground distance between arcs (R_5, R_6) is shown in the inset of Figure 6 and is labeled D_6 . Arcs (R_5, R_6) can be seen to be specified as:

$$\begin{aligned} Y_{ij5}^2 + Z_{ij5}^2 &= R_5^2 \\ Y_{ij6}^2 + Z_{ij6}^2 &= R_6^2 \\ R_6 &= R_5 + \frac{CT}{2} \end{aligned} \quad (17)$$

where the coordinate system is set-up such that $x = 0$, values for R_5 and R_6 can be determined from system and mission parameters such as pulse length, altitude, near range angle or incidence, etc., the (Y_{ij5}, Z_{ij5}) and (Y_{ij6}, Z_{ij6}) are the range (j) and elevation (Z) coordinates of data base points satisfying the criteria. In this scheme the data base is oriented orthogonal to the flight - direction so that the antenna bore-sights down a column of constant azimuth ($x = 0$) thereby allowing variations only across range ($Y = j$) and in the elevation (Z) dimension.

Thus, it is easily determined via equations (17) which data base points, for a given azimuth column, are closest to where R_5 and R_6 intersect the terrain profile. The data base points belonging (in the range-direction) to resolution cell A_6 are those plus the ones falling between them. The ground distance in the range - direction for resolution cell A_6 can be approximated by the straight line connecting the points $(Y_{ij5},$

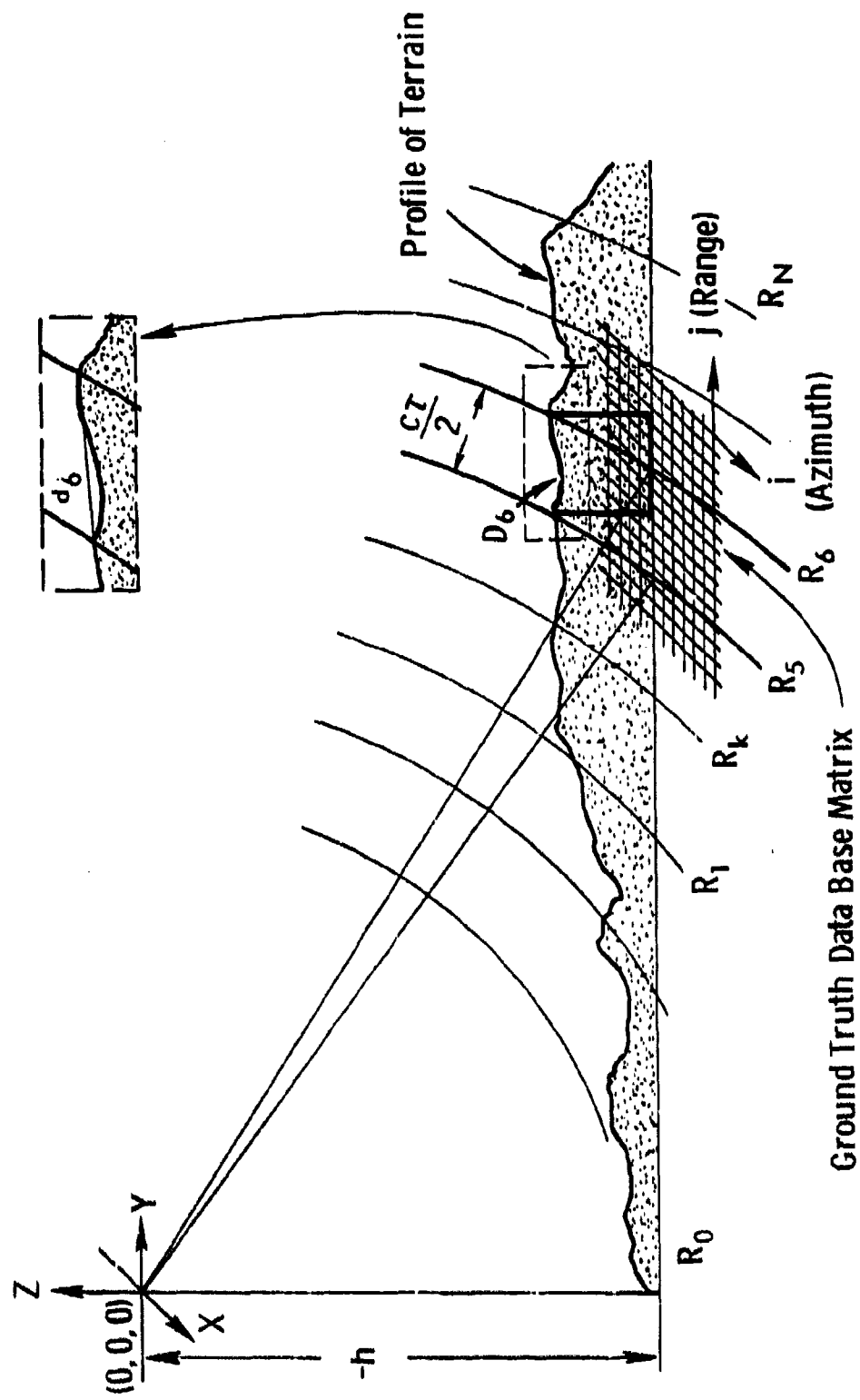


Figure 6. Range Resolution

Z_{1j5}) and (Y_{1j6}, Z_{1j6}) . The length of that line (d_6) is specified as:

$$d_6 = \sqrt{(Y_{1j6} - Y_{1j5})^2 + (Z_{1j6} - Z_{1j5})^2} \quad (18)$$

In general, for a given azimuth column in the data base (i), the coordinates of the bounding points of resolution cell (A_k) can be specified as $(x=0, Y_{1jk-1}, Z_{1jk-1})$ and $(x=0, Y_{1jk}, Z_{1jk})$ where K is used to denote which radar resolution cell is being evaluated. The appropriate points can be selected from

$$Y_{1jk-1}^2 + Z_{1jk-1}^2 = R_{k-1}^2 \quad (19)$$

$$Y_{1jk}^2 + Z_{1jk}^2 = R_k^2 \quad (20)$$

$$R_k = R_{k-1} + \frac{c\tau}{2} \quad (21)$$

$$d_{1k} = \sqrt{(Y_{1jk} - Y_{1jk-1})^2 + (Z_{1jk} - Z_{1jk-1})^2} \quad (22)$$

where the results are subscripted with an i to denote that these data all come from a column of constant azimuth.

Figure 7 illustrates the geometry for a radar system employing a narrow beamwidth antenna. For such systems the half-power azimuth resolution is specified by $\beta_h R$. Figure 7 shows the half-power contours plotted in the (y,-h)-plane. The terrain bounded in the range-direction by the arcs (R_5, R_6) , as previously discussed, and in the azimuth-direction by the half-power contour is shown. The half-power antenna contours define the azimuth extent of the radar resolution cell.

Previously, we located the data base points coinciding with the arcs (R_5, R_6) as (Y_{1j5}, Z_{1j5}) and (Y_{1j6}, Z_{1j6}) for a particular azimuth column ($x=0$). Now we want to fix range at those points and search across rows of azimuth (both in the $\pm x$ -direction, increasing as well as decreasing i) for the intersection of the half-power antenna contour with the terrain. The method is straight forward.

Start with the data base point $(X_{1j6}, Y_{1j6}, Z_{1j6})$, which is the intersection point of R_6 with the terrain ($X_{1j6}=0$). Fix $j = j_6$ so that Y_{1j6}

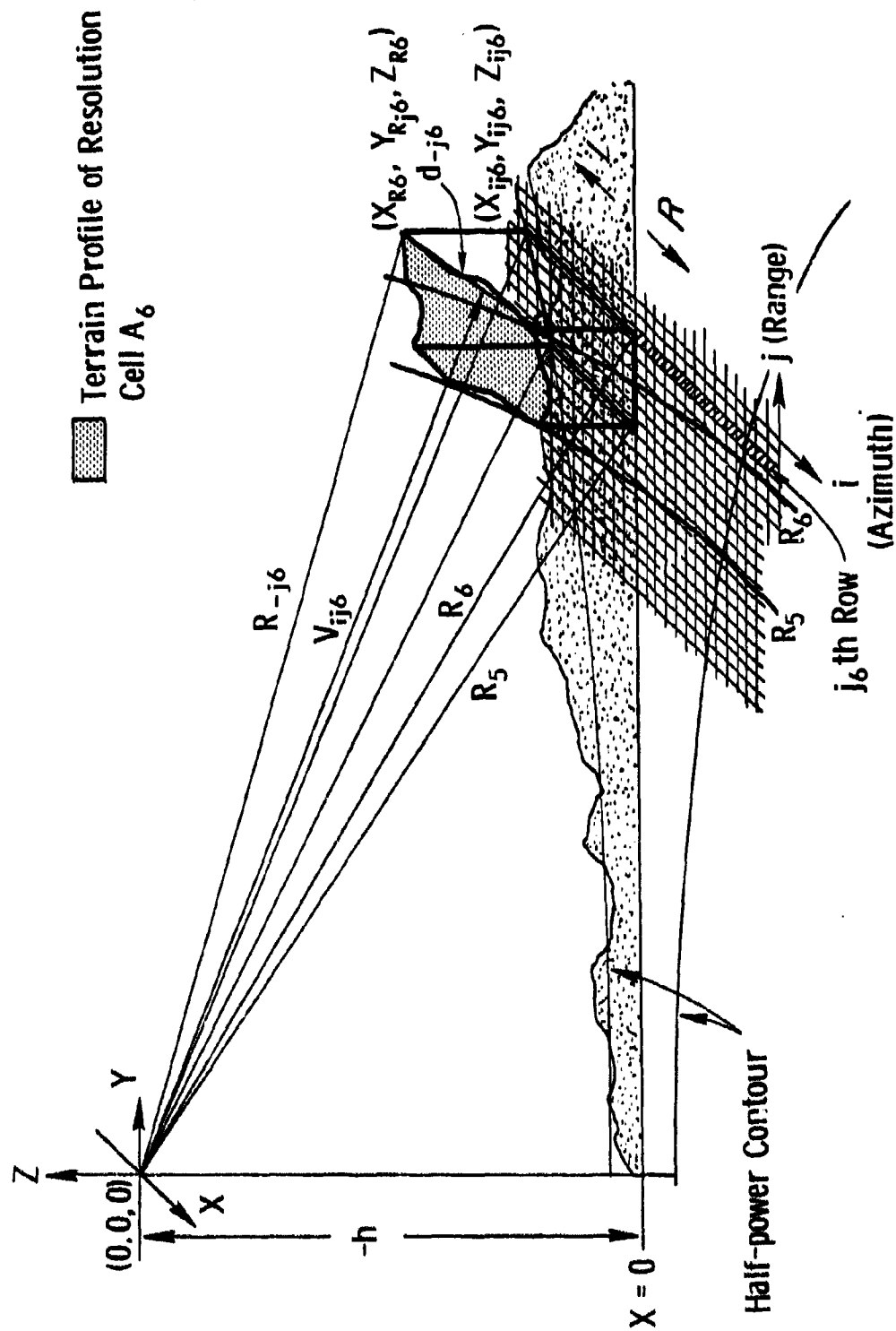


Figure 7. Azimuth Resolution

will not be allowed to vary, and test data base points in the -x- direction of the j6 row (row of constant range). We know that the intersection of the half-power contour with the terrain will be a distance (d_{Lj6}) from R_6 as shown in Figure 7 and will be specified by

$$d_{Lj6} = \frac{R_{Lj6} R_h}{2} \quad (23)$$

where R_{Lj6} is the range from the radar antenna to the terrain in the j6-th azimuth data base row corresponding to the outer boundary of radar resolution cell Δ_6 . We don't know R_{Lj6} but we can find it and, having done this, determine where the half-power contour of the antenna pattern intersects with the terrain. To do this we test each data base point in the -x-direction (azimuth, or decreasing i).

Figure 7 shows that a vector (\vec{V}_{ij6}) can be constructed from the radar antenna (0,0,0) to each data base point ($X_{ij6}, Y_{ij6}, Z_{ij6}$) as follows ($X_{ij6} \neq 0$)

$$\vec{V}_{ij6} = (X_{ij6})\hat{x} + (Y_{ij6})\hat{y} + (Z_{ij6})\hat{z} \quad (24)$$

where ($X_{ij6}, Y_{ij6}, Z_{ij6}$) = Coordinates of each point to be tested;

($\hat{x}, \hat{y}, \hat{z}$) = Unit vectors in the X-, Y-, Z-directions, respectively.

The magnitude of this vector is just the range (R) from the radar to the ground

$$R = |\vec{V}_{ij6}| = \sqrt{(X_{ij6})^2 + (Y_{ij6})^2 + (Z_{ij6})^2} \quad (25)$$

Calculate the half-power distance (d_{-j6}) this range would predict if $R_{Lj6} = R$ in equation (23) and compare to the distance (d_m) from the R_6 arc to this point

$$d_m = |X_{ij6}| \quad m = L, R \quad (26)$$

where the x-coordinate of the intersection of the R_6 arc with the terrain is, by definition, equal to zero, and X_{ij6} is the x-coordinate of the point being tested. Subtract d_l (equation 25) from d_{Lj6} (equation 23) and decide whether the point under test represents the boundary of the antenna pattern

as follows

$$\begin{aligned}
 \text{If } d_{Lj6} - d_i &> 0 \quad \text{test next point;} \\
 \text{If } d_{Lj6} - d_i &= 0 \quad \text{half-power contour point;} \\
 \text{If } d_{Lj6} - d_i &< 0 \quad \text{outside the half-power contour point.}
 \end{aligned} \tag{27}$$

This test allows determination of the data base points and the coordinates which define the boundary of the antenna pattern half-power contour in the $-x$ -direction, call them (X_L, Z_L) . Repeat the test in the $+x$ -direction (increasing i) for determination of the data base points which define the boundary on that side, call them (X_R, Z_R) .

In this way it is easily determined via equations (27) which data base points, for a given row of range (j) in the data base, are closest to where the antenna pattern half-power contours, in 30th the $\pm x$ -direction (i), intersect the terrain. The data base points belonging (in the azimuth direction) to resolution cell A_6 are those plus the ones falling between them. The ground distance in the azimuth-direction can be approximated by

$$\begin{aligned}
 d_{15} &= \sqrt{(X_{R5} - X_{L5})^2 + (Z_{R5} - Z_{L5})^2} \\
 d_{16} &= \sqrt{(X_{R6} - X_{L6})^2 + (Z_{R6} - Z_{L6})^2}
 \end{aligned} \tag{28}$$

In general, for a given range row in the data base (k), the coordinates of the bounding points of resolution cell (j) can be specified from

$$\begin{aligned}
 d_{mjk} &= \frac{R_{mj} \beta h}{2} & m = L, R \\
 R &= (X_{mjk})^2 + (Y_{mjk})^2 + (Z_{mjk})^2 & m = L, R \\
 d_m &= |X_{mjk}| & m = L, R
 \end{aligned} \tag{29}$$

and the test

$$\begin{aligned}
 \text{If } d_{mjk} - d_i &> 0 \quad \text{test next point;} \\
 \text{If } d_{mjk} - d_i &= 0 \quad \text{half-power contour point;} \\
 \text{If } d_{mjk} - d_i &< 0 \quad \text{outside half-power contour point;}
 \end{aligned} \tag{30}$$

where $m=L, R$.

The distance across the cell at each edge can be specified by

$$d_{ik} = (x_{RK} - x_{LK})^2 + (z_{RK} - z_{LK})^2 \quad (31)$$

If it is desired to determine the area represented by the radar resolution cell instead of simulating multiple categories within the cell, this can be accomplished in many ways. One way is to calculate the area from the trapezoidal shade described by successive applications of equations (29), (30), and (31) for both range edges of a resolution cell. Another way is to find the azimuth extent only for the middle of the resolution cell (eg., for the point $(\frac{y_{ijk} + y_{ijk-1}}{2}, z_{ij})$). If we do this, call the distance across the cell in the azimuth direction s_j where

$$s_j = d_i \left(\frac{k+(k-1)}{2} \right) \quad (32)$$

as given by equation (31). This situation is depicted in Figure 8.

The area of the resolution cell (A_k) is given by

$$A_k = d_{ik} s_j \quad (33)$$

where: d_{ik} = Given by Equation (22);

s_j = Given by Equation (32).

In terms of the coordinates of the bounding points, this can be rewritten as:

$$A_k = \sqrt{\left[(y_{ijk} - y_{ijk-1})^2 + (z_{ijk} - z_{ijk-1})^2 \right] \left[(x_{RK} - x_{LK})^2 + (z_{KK} - z_{LK})^2 \right]} \quad (34)$$

where: A_k is the area of the k^{th} resolution cell.

This expression for the area of a resolution cell is again an approximation to the real area but it isn't as gross as the approximation of Equation (16).

But, for this expression to be reasonably accurate, it is necessary that the slope of the terrain not change much in either the range or azimuth directions from that calculated for the center of the cell.

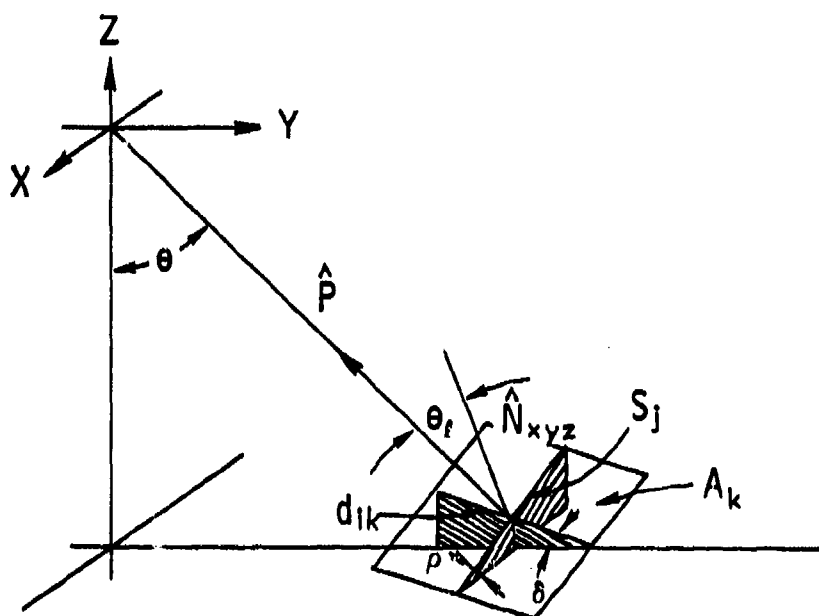


Figure 8.

Resolution Cell with Arbitrary Slope (Plane Facet)

Figure 8 shows an illustration of the idealized resolution cell. It can be seen that the cell is modeled as a plane facet having sides of length d_{ik} and s_j and, thus, area A_k . From the geometry of Figure 8 it can be shown that the local angle of incidence (θ_l) is given by

$$\theta_l = \cos^{-1} [\mathbf{P} \cdot \mathbf{N}_{xyz}] \quad (\text{Dot Product}) \quad (35)$$

where: $\hat{\mathbf{P}}$ = Unit vector pointing from the center of the resolution cell through the antenna boresight;

$\hat{\mathbf{N}}_{xyz}$ = Unit vector normal to the resolution cell.

Also, it can be seen that the unit normal is given by

$$\hat{\mathbf{N}}_{xyz} = \frac{\mathbf{s}_j \times \mathbf{d}_{ik}}{|\mathbf{s}_j \times \mathbf{d}_{ik}|} \quad (36)$$

where: $\mathbf{d}_{ik} = \hat{\mathbf{y}} + (\tan \delta) \hat{\mathbf{z}}$ = "Tilt" in the range direction;
 $\mathbf{s}_j = \hat{\mathbf{x}} + (\tan \rho) \hat{\mathbf{z}}$ = "Tilt" in the azimuth direction.

This important result was derived previously¹. It is important because the point scattering simulation model basically uses empirical backscatter data to model the electromagnetic properties of the ground and these data are a function of the effective local angle of incidence (θ_g) of each patch of ground, resolution cell, with respect to the antenna.

These results can be extended to cases requiring finer resolution than the fundamental limits imposed by the resolution cell concept. Basically, they involve terrain profile following in two dimensions. "Instantaneous" (much smaller) resolution cells can be determined and the ranges, areas, and angles of incidence can be calculated. These data can be used to determine the "instantaneous" power and phase from each little resolution cell. These data, power, and phase, can then be added appropriately (as in synthetic aperture radar). Or, many other approaches can be used successfully. However, as a general rule, the more precisely the terrain profile is followed, the more expensive simulation and data base construction become. For these reasons, most data bases, and thus simulations produced from the point scattering method, are made using as many simplifying assumptions as possible.

1.4.2 Validity of Differential Scattering Cross-Section Concept

1.4.2.1 Explanation of Empirical σ^0 Data

The point scattering radar image simulation method uses both empirical backscatter data (differential scattering cross-section, σ^0) and theoretical results to model the radar return from terrain. Empirical data (σ^0) are used wherever possible because the return from terrain is very complex and extremely difficult to model theoretically. These empirical σ^0 data are taken from an extensive agricultural/soil moisture bank under development

¹ Holtzman, J. C., V. H. Kaupp, R. L. Martin, E. E. Komp, and V. S. Frost, "Radar Image Simulation Project: Development of a General Simulation Model and an Interactive Simulation Model, and Sample Results," TR 234-13, Remote Sensing Laboratory, The University of Kansas, February, 1976.

at the Remote Sensing Laboratory⁴. This data bank consists of σ^0 measurements stratified by frequency, polarization, soil moisture, agricultural type, plant height, and growing season. It is the availability of this data bank which has made possible the wide range of applications for which the point scattering method has been used. Supplementary data have been taken from the literature¹⁰ and theoretical models have been examined to extend and extrapolate the available empirical σ^0 data to other frequencies, polarizations, scattering categories, and look directions. To complete the other side of a circular argument, the successful simulation of radar images by the point scattering method speaks eloquently for the great value of empirical data banks and argues emphatically for a greater effort to build these data banks. Availability of such data banks will to a large extent determine the applications for which radar image simulation can be used in the future. If there are large programs waiting in the wings, so to speak, to use simulation, a σ^0 data collection program needs to be started to measure the differential scattering cross-sections of the various scattering categories expected to be in the terrain envelope of which this program will operate.

The radar return from terrain varies with a large number of parameters of both the radar system and the properties (dielectric and geometric) of the terrain. These parameters interact to produce the radar return from each portion of the ground. Some of the more important of these parameters are listed in Table 1. These parameters and their interactions must be modeled accurately in order to simulate the radar return from terrain. The model used to describe the ground parameter interaction is the differential scattering cross-section (σ^0) rather than the total cross-section (σ) used for discrete targets. The differential scatter-

⁴ Bush, T. F. and F. T. Ulaby, "Fading Characteristics of Panchromatic Radar Backscatter from Selected Agricultural Targets," IEEE Trans. Geosci. Electron., Vol. GE-13, October 1976, pp. 149-157.

¹⁰ Peake, W. H., and T. L. Oliver, "The Response of Terrestrial Surfaces at Microwave Frequencies", Technical Report AFAL-TR-70-301, Air Force Avionics Laboratory, Wright Patterson AFB, May, 1971.

Table 1. Radar System/Ground Return Interaction Parameters

A. Radar System Parameters

1. Transmitted Power;
2. Wavelength of Illuminating Energy;
3. Polarization of Illuminating Energy;
4. Illuminated Area (Related to the duration of the pulse of illuminating energy and the geometry of the transmit/receive antenna);
5. Direction of the Illuminating Energy.

B. Ground Return Parameters

1. Complex Permittivity (Conductivity and permittivity);
2. Roughness of Surface Relative to Wavelength of Illuminating Energy;
3. Roughness of Subsurface to Depth where Amplitude of Illuminating Energy is Attenuated to Negligible Amount;
4. Shape and Orientation of Surface and Subsurface Structure Relative to Wavelength and Direction of Illuminating Energy.

ing cross-section is normally used because it describes the radar return independent of the area of illumination. The total cross-section (σ) for terrain varies with the area of illumination. For the most part, the total cross-section is used for discrete targets which, at normal radar ranges, are smaller than the resolution element of the radar. For discrete targets, σ is a reasonable model. For terrain, the variation of σ with the area of illumination makes σ an intractable model for the electromagnetic properties of the ground. The differential scattering cross-section (σ^0) is defined to be a description of the radar return per unit area thereby eliminating dependence of the ground model on the area of illumination. Use of σ^0 is necessary to make radar image simulation of terrain tractable*.

1.4.2.2 Application of Empirical σ^0 to Distributed Targets

The point scattering model for radar image simulation has been developed to be specifically applicable to simulation of the radar return from terrain. The model is not limited to terrain, terrain is its simulation forte. In particular, the model is especially applicable to terrain which can be modeled as collections of homogeneous regions which are large compared with the radar resolution element such as fields, forested areas, etc. Such areas are called distributed targets. With distributed targets as the model for the terrain, the point scattering simulation model reduces to the particularly simple form of Equation (5); Section 1.4. This simplification of the model is produced by the arguments leading to the use of Equation (7) instead of either (8) or (9), Section 1.4.1.1,

*Note: This discussion does not imply that the power received at the antenna which was reradiated from the terrain is independent of the area of illumination. In fact, the return power is proportional to the summation of the differential scattering cross-section multiplied by the differential area of each scattering center ($P \propto \sum_{i=1}^N \sigma_i^0 \Delta_i$). What

this discussion means, instead, is that one degree of freedom (dimension) has been removed by the use of σ^0 instead of σ in the ground return model. Specifically, σ^0 is independent of item A4 listed in Table 1. However, this dependence is properly accounted for by the point scattering radar image simulation model; see Section 1.3.1.1.

for the equation governing the radar system and ground interaction problem. Those arguments will not be repeated here. Only the salient points of interest are discussed.

The notions of homogeneity of the distributed targets and their size compared to a radar resolution cell are important. With these qualifications and the statistical property of random location in the ground cell of a large number of scattering centers, an average value of the differential scattering cross-section can be used (instead of the actual σ^0 value for each scattering center within the resolution cell). The importance of these requirements are immediately obvious upon noting that all empirical σ^0 values contained in the RSL data bank and most reported in the literature have been measured in accordance with these properties. They (the empirical data) represent the average value of σ^0 of all the scattering centers located within a homogeneous region which is larger than the resolution element of the measuring radar system. For this very important reason, empirical differential scattering cross-section data are an exceptionally good model of the radar return from terrain for radar image simulation. The empirical data are valid representations of the radar return from terrain until one of the necessary assumptions (homogeneity, cell size, number of scatterers, placement of scatterers) is violated. This means that empirical data can be used for simulation over an extremely wide range of radar systems and terrain types. For a number of cases where one or more of the necessary conditions is violated, an evaluation of the radar system ground properties, and use of the simulated image may show that it is reasonable to use empirical data to approximate the scattering properties of the scene. Other situations may show that cleverness of implementation of the simulation model will allow use of empirical data where it otherwise would be unsuitable. These comments aside, the point to be made is that empirical σ^0 data are exactly the right model to use for the ground radar returns from the scenes to which the point scattering radar image simulation model is best applied. No general rules have yet been identified which relate resolution cell size or homogeneity, number, and placement of scatterers to the suitability of using empirical data for the ground return model.

This is not to say that empirical data are a panacea for the radar image simulation problem. It is not reasonable to expect to measure σ^0 for all possible combinations of frequency, polarizations, scattering types, seasonal variations, growing seasons, etc.; the dimensions of the problem are too large. In addition, variations in calibration techniques used by different researchers results in variations in the accuracy of σ^0 reported in the literature. Theoretical scattering models are very much a necessity to extend and extrapolate the data that are measured to other conditions.

1.4.2.3 Accuracy of Empirical σ^0 Data

One final question needs to be examined in this discussion of the validity of using differential scattering cross-section data to model the radar ground return: The question of accuracy of the empirical data. This is a very difficult question to assess because there are rarely clear and unambiguous definitions of accuracy. Certainly, for radar image simulation results to be realistic, the σ^0 data must be accurate. But accurate here means two different things: (1) Accuracy of the empirical data, (2) accuracy of specification of the scattering types in the scene. The first type of accuracy is the one of importance to this discussion. The second type is controllable by the exercise of care in being meticulous in specifying terrain types and boundaries when ground truth data bases are built as well as acquiring good ground truth when empirical σ^0 data were originally collected. This accuracy of specification of the scattering categories in the data base is directly related to the time, effort, and resources expended to construct each data base.

The question of the accuracy of the empirical data is another matter. Generally, accuracy can be separated into two parts: Relative and absolute accuracy. Relative accuracy is here considered to be represented by the bias error (offset) between the measured value and true value of σ^0 . Absolute error is considered to be the statistical fluctuations of the measured data. With these definitions in mind, then, the relative error would be the difference between the mean value (central tendency) curve

and true value curve while the absolute error would be the variation of each average value from the central tendency.

On the assumption that, given the definitions, the absolute error of the empirical data is strictly less than the error of specification of scattering types and boundaries in the data base, this type of error is insignificant. On the other hand, relative error is significant. If all empirical data used in the simulation of a scene were measured by the same system, then the relative error could be easily calibrated out of the simulated image, or, if a calibrated image is not necessary, it could be safely ignored. If empirical data collected by different systems are mixed to produce a simulated image, it will be necessary to evaluate the results against some standard having the proper radar parameters such as a real image of a scene containing the suspected categories. This comparison can be used to identify empirical data sets having bias errors. These bias errors can then be traced to the source and the matter resolved. In fact, this evaluation of σ^0 data has been done for some of the empirical data sets used to produce simulated radar images in the work reported in this document.

Therefore, it needs to be reiterated that empirical differential scattering cross-section data together with theoretical scattering studies form a very good model for the microwave electromagnetic properties of the ground. Absolute accuracy of σ^0 is insignificant compared to data base accuracy. Relative errors can be either removed by calibration, or safely ignored for some applications, or identified and corrected.

1.4.3 Validity of the Data Base Concept

The point scattering radar image simulation model is ideally suited for implementation on the digital computer. This implementation of the model explicitly means that a continuous process (operation of imaging radar) is being approximated by a discrete process (simulation by digital computer). The ramifications of this approximation must be evaluated on a simulation by simulation basis.

Short-pulse-length imaging radars are continuous processes. A short pulse of energy traveling at the speed of light and having a wavelength in the microwave portion of the electromagnetic spectrum is radiated to the ground confined by a directional antenna to illuminate only a narrow strip. This beam of energy is confined in the azimuth direction by the physical width of the antenna and in the range direction by the length of the pulse. A fraction of this energy is reradiated from the ground back to the antenna. The receiver processes the received energy by the time of arrival; the energy reradiated from closer features will be received and processed sooner than the energy from features which are farther away. The output of the receiver is a video signal which represents the intensity profile versus time (and, thus, distance) of the energy reradiated from the ground. This video signal can be used to intensity modulate the electron beam of a cathode ray tube (CRT) for a real aperture system and the radar image can be built pulse by pulse. The process just described is continuous in the range direction and is discrete in the azimuth direction. Each pulse of energy illuminates the entire length of the swath being imaged in the range direction. The reradiated energy returning from a given range sweep is continuously processed versus time and the resultant video signal represents one sweep across the CRT (one range sweep). The width in the azimuth direction of each range sweep is defined by the physical length of the directional antenna. Entire scenes are built up of the range sweeps corresponding to a large number of individual pulses as the aircraft (or satellite) carrying the radar moves across the scene. The rate at which individual pulses are transmitted, received, and processed is known as the PRF (Pulse Repetition Frequency). The PRF together with the velocity of the vehicle defines the number of samples per unit distance (number of range sweeps)

in the azimuth direction which are collected. The sampling rate is normally quite high meaning that the vehicle moves only a very small incremental distance between pulses (range sweeps) and the scene is thus over-sampled. This is the process which is being modeled by the point scattering simulation method. (To simulate a SAR - Synthetic Aperture Radar - the appropriate steps would be taken to achieve sufficient azimuthal sampling.)

The basic simulation model hinges around the concept of a minimum resolution element. For short-pulse radars, the minimum resolution distance in the range direction is defined to be proportional to the length of the transmitted pulse of energy. For narrow beamwidth radars, real or synthetic, the minimum resolution distance in the azimuth direction is defined to be proportional to the physical length of the antenna. The minimum resolution element, or cell, is then defined to be the area on the ground described by the product of these two resolution distances (range x azimuth)⁵. This concept of a resolution cell relates to real imaging radars and insofar as the pulse length is short and the antenna beamwidth narrow, the resolution cell concept is a good approximation to reality. The resolution cell concept lends itself very nicely to the problem of modeling a real, continuous, process. The specific details of calculating the cell size for simulation purposes were discussed in previous sections (1.4.1.2 and 1.4.1.3).

Having discussed the validity of using resolution cells to properly model the operation of real imaging radars, it is now necessary to discuss the ramifications of modeling the scene as a collection of discrete cells. Recall that the point scattering model is ideally suited to simulate the radar returns from distributed terrain. This means that the terrain is modeled as consisting of homogeneous regions which are larger than the radar resolution cell. Given this as the situation, then it can be seen that it is entirely reasonable to model the terrain as discrete cells so long as each cell is at least as small as the radar resolution cell. If either condition is not met for specific cases (terrain can be modeled

⁵Reeves, R. G., A. Anson, and David Landen, Manual of Remote Sensing, Vol. 1, Chapter 9, American Society of Photogrammetry, Falls Church, Virginia.

as homogeneous regions, and resolution cell is smaller than an homogeneous region) then the point scattering simulation method may not be applicable for those cases. However, a case-by-case evaluation will show whether it is reasonable to go ahead and use the model to approximate the actual situation, or to modify the model, or to salvage the situation in some other way.

Over the range of resolutions that the basic model and supporting data (σ^0) are valid, it is reasonable to model the ground as a matrix of independent homogeneous regions which are at least as small as the resolution cell of the radar being simulated. This matrix of data is called a ground truth data base and includes (at least) the scattering type, and position and elevation for each cell. This simple model of the ground (ground truth data base) works well over the middle range of radar resolutions. In this range, the resolution cell size is sufficiently small that the scene is adequately sampled to permit complete visual restoration of the scene. It needs to be emphasized that complete visual restoration means that the simulated scene has data points spaced close enough relative to the wavelength of the transmitted energy and relative to changes in the terrain that the resultant image "looks" continuous just as does a real radar image of the same scene. Toward either extreme of resolution (either very fine or very coarse) this model breaks down. At the coarse resolution extreme, the sampling of the scene becomes spaced too far apart and the simulated radar image takes on a very blocky appearance. The answer to this problem is to make each element of the ground truth data matrix smaller than the size of the radar resolution cell and then combine the returns from (weighted by antenna pattern) an appropriate number of cells to make up a resolution cell. This approach was utilized to great effect in Section (4.0) and, in fact, can be used for simulating any resolution radar. At the other extreme, very fine resolution, the problems of constructing a data base with the requisite fineness become enormous. And, at the far extreme, the model begins to breakdown because one or more of the basic tenets are violated; for instance, the number of independent scattering centers in a resolution cell become too few for Equation (7) to be valid. But, for the vast majority of cases, the concept of modeling the ground by a ground truth data matrix remains valid.

1.4.4 Validity of the Radar Receiver Model

As was previously stated, the point scattering radar image simulation model was derived from the closed system model consisting of ground scene, radar system, and image medium. The dielectric properties of the ground are essentially modeled by the differential scattering cross-section (Section 1.4.2) and the location, elevation, and scattering type of each point on the ground are modeled by a ground truth data matrix (Section 1.4.3). The radar system and ground property parameter interactions are modeled by the radar equation (Section 1.4.1). The next step is to model the actual transfer function of the radar receiver it is desired to simulate. Once this step is performed and the receiver transfer function is incorporated into the software implementation of the basic point scattering model, the model is then designed for a specific application. For the purposes of this report it was assumed that the receiver transfer function was linear. That is, it was assumed that the average power returned to the antenna terminals as calculated by the radar equation differs from the power out of the receiver only by a constant which can be seen to be a scaling factor. Another way of saying this same thing is that the intensity (I) out of the receiver is given by:

$$I = MP_R \quad (37)$$

where: P_R = Value of the return power referenced to the antenna terminals (Equation (2) or (3));

M = Constant = Receiver transfer function (same as M_1 in Equation (5)).

This simple model most certainly is not exact. But, for the work reported here it was an unnecessary additional expense of computational complexity and computer costs to model, explicitly, the receiver transfer function. Incorporation of a real receiver transfer function would be very straightforward. No significant degradation of these results was caused by using a linear model for the receiver. In fact, the receiver transfer function really only becomes important where the receiver significantly departs from linearity. For the most part,

the results reported here were produced for 20 dB of the center portion of the dynamic range normally available in an imaging radar. This is the region where the linearity assumption is most valid. To take the argument one step farther, a real receiver transfer function becomes important in either highly non-linear receivers (or those portions of their dynamic range) or in cases where it is necessary to produce calibrated, simulated radar images with a specified absolute accuracy.

1.4.5 Validity of the Image Medium Model

Discussion of the image medium will complete this discussion of the assumptions, limitations, and constraints of the point scattering radar image simulation model. This is the final portion of the closed system model referenced in Section (1.4.4). The basic model can be set-up for any imaging medium. But, the model reported in Equation (5) is set-up for film to be the final product. This is a very reasonable imaging medium in the light of the fact that all the results reported in this report are photographs. The basic properties of film and the relationship of film to power are taken from Goodman³. The intensity (I) of the radar signal out of the receiver is related to the density (D) of silver grains in the emulsion of film by:

$$D = \gamma \log_{10} I + \log_{10} k \quad (38)$$

where: γ = Film gamma = Transfer function of film;

k = A positive constant which depends upon the exposure time and on the film processing and development.

With the result of Section (1.4.4), the radar receiver transfer function (M) can be incorporated into Equation (38) by using Equation (37) and substituting for the intensity (I) as follows:

$$D = \gamma \log_{10} \bar{P}_r + \gamma \log_{10} M + \log_{10} k \quad (39)$$

³ Goodman, J. W., "Introduction to Fourier Optics," McGraw-Hill, Inc. 1968.

This relationship is true only in the linear portion of the transfer function of film. This condition is easily met by scaling the return power to the linear portion of the dynamic range of the film, and by bracketing each scene with a sufficient number of exposures to insure that a good one was taken.

A penalty is imposed on the model by the selection of ordinary film as the image medium. The dynamic range of film is something less than 20 dB while the dynamic range of a typical scene of terrain may be 60 dB and possibly as much as 80 dB. Obviously, with film as the image medium, at most 20 dB of this range is attainable. The 20 dB of interest can be selected by proper adjustment of various constants in the model. (eg., G_{RC} , g , and the return power from a point: Equation 5).

For present purposes, the model implemented relating the detected intensity out of the radar receiver to the density of the silver grains in the film emulsion is reasonable. Any other imaging medium can be used with the point scattering model providing the appropriate transfer function is incorporated.

2.0 SLAR SIMULATION AND VALIDATION

The purpose of this section is two-fold: (1) Enumeration and description of the activities at RSL within the contract year resulting in simulation of side-looking airborne radar images, and (2) Validation, both quantitative and qualitative, of the point scattering method and its software implementation. The scope of the work is limited to two validation scenes (simulated radar images), produced from two sets of flight parameters, one radar system model, and two data base sites. Real imagery purchased solely for the validation task was obtained in a SLAR format (Goodyear, model number APD-10, synthetic aperture radar, resolution 10 feet by 15 feet), but not for PPI (Plan-Position Indicator) format. The effort involved in SLAR validation is, thus, a one step process (i.e., compare the simulated to the real radar imagery). The result of the validation will be discussed later in Subsection 2.5.

2.1 Work Plan

The successful completion of the SLAR tasks depended upon several interrelated activities: (1) Selection of a suitable terrain site; (2) Production of a data base; (3) Formation of a sufficient catalogue of empirical or theoretical ground return data (σ^0); (4) Development and refinement of the digital implementation of the point scattering method; and (5) Simulation of radar imagery.

The first category of work, selection of a test site, depended upon the satisfaction of several criteria by the site. Since the validation was envisioned to consist of a comparison between real and simulated imagery, it was known that the flight and system parameters of the real and simulated radars should coincide to the greatest degree possible. The foremost criteria for the selection process naturally became: (1) Real radar image data of the test site must exist; (2) The test site should be representative of a wide variety of radar categories; (3) Elevation and planimetric data should be obtainable; (4) A resource for identifying the radar categories within the planimetry map must exist (e.g., aerial photograph);

and (5) Empirical differential scattering cross-section data (or theoretical scattering models) for the categorized scattering types within the test site should be available. The Pickwick Dam site met the criteria (1) through (4), and was selected for the year's efforts. Though an insufficient catalogue of differential scattering cross-section data was found to exist in the RSL data bank for the categories within the Pickwick site, this problem was resolved¹¹ by appeal to the literature, theory, and extrapolation of empirical data, and in part by intuition. Although the current catalogue of σ^0 data is considered far from the most desirable set, it has allowed experimentation and validation to proceed with good results.

Prior to initiation of efforts toward the second task, production of a data base, the real radar system being used for validation was considered. For verification purposes the system, resolution and flight parameters of the real radar were being mimicked to a reasonable extent. However, simulating the very fine resolution of the real radar was regarded to be computationally and time-wise unwieldy, and neither elevation nor planimetric data were available at the resolution of the APD-10 system. The unknown factor involved in construction of the data base was the number of data points whose properties should be combined to determine the properties of a resolution cell. The decision was made to take full advantage of the available elevation data (a rectangular grid matrix with a resolution in both dimensions of 6.25 meters or 20.51 feet). The simulated resolution was chosen to be 60 feet x 60 feet^{*} so the planimetric detail in the ground truth data base was designed to be fine enough so that the simulated imagery would contain the same category information that would appear in imagery gathered by an actual 60 foot resolution system. The matrix method of symbolically representing terrain for simulation purposes is a discrete sampling, and the digital simulation of radar imagery is a reconstruction process. Future studies must determine the sampling interval needed for the terrain properties of elevation and backscatter response. The lower bound of data

¹¹ Abbott, J. L., R. L. Martin, M. McNeill, V. H. Kaupp, and J. C. Holtzman, "Backscatter Data for the Digital Radar Image Simulation of the Pickwick, Alabama Site," TR 319-7, Remote Sensing Laboratory, The University of Kansas, February, 1977. Included in Appendix G, Vol. II, ETL TR-0118.

^{*} Note the use of square resolution cells, independent of radar range. This assumption is explained in Section 1.4.1.3.

point density has not been determined, but it has since been observed that the current practice of using approximately nine data points per resolution cell is more than adequate, based on the quality of simulated images. With the expectation that 6.25 meter data base resolution would be fine enough for the ultimate goal of simulating a 60 foot resolution system, the production of the data base resumed.

Elevation data stored on computer-compatible digital magnetic tapes were obtained from ETL. Extraction of the radar planimetry data from maps and aerial photographs was pursued.¹² This effort consisted of delineation and categorization of homogeneous areas (at microwave frequencies) of the test site. Both cultural targets (those incapable for various reasons of being characterized by a differential scattering cross-section) and area-extensive, "distributed" targets were identified. A digitized form of the planimetry and data was organized into a two-dimensional matrix compatible with the elevation data. The digital planimetry and elevation matrices were merged and stored on magnetic tapes.¹³ The information contained on the tapes is referred to as the ground truth data base because the matrix describes both the geometric and electromagnetic properties of the terrain (in sampled, discrete form), and the point scattering method uses only this information about the terrain to describe the "radar version" of the scene.

Simultaneously, goals (3) and (4) were achieved, that is, the microwave reflectivity data were gathered and the implementation software was refined. The majority of σ^0 data deemed useful was generated at RSL, where an extensive agriculture/soil moisture data bank exists.⁴ The resources for theoretical scattering models were also found at RSL. The computer package which was produced by the Kansas simulation group was structured for computational and trouble-shooting efficiency. The point scattering method embodied in the programs is general in the sense that for any radar system model, any flight parameters and any ground truth data base, imagery can

¹² Davison, E., V. H. Kaupp, J. C. Holtzman, "Increased Resolution of Planimetric Data Base: Pickwick Site", TR 319-21, Remote Sensing Laboratory The University of Kansas, March, 1977. Included in Appendix E, Vol. II, ETL TR-0118.

¹³ Komp, E., J.L. Abbott, V.H. Kaupp, J.C. Holtzman, "Improved Resolution Digital Ground Truth Data Base: Pickwick Site", TR 319-21, Remote Sensing Laboratory, The University of Kansas, August, 1977.

⁴ Bush, T.F. and F.T. Ulaby, "Fading Characteristics of Panchromatic Radar Backscatter from Selected Agricultural Targets," IEEE Trans. Geosci. Electron., Vol. GE-13, October 1976, pp. 149-157.

be generated. In an operational environment, it is advantageous to adapt the general simulation package to the specific application. To accomodate a certain radar and data base, the computer software can be greatly simplified, resulting in time and cost savings.

Upon the successful achievement of the goals (1) through (4), the remaining goal was to produce simulated imagery in the form of strip maps and to judge its performance. Within the test site two large swaths were "imaged" by the simulated radar, and these areas correspond exactly to two swaths imaged by the real radar for which imagery was purchased. The simulation process consists of running the computer programs and supplying the ground truth data base as an input which is read into the computer. The final output of the computer programs is a magnetic tape containing "Image data". The images produced are reported in Subsection 2.5 in addition to the validation imagery and brief analyses.

2.2 SLAR Validation Data Base

A ground truth data base was constructed of the topographic area in the states of Tennessee, Mississippi, and Alabama for a square centered on the northwest corner of the Power House Building at the Pickwick Landing Dam across the Tennessee river. After specification of the test site and radar system parameters, source data were acquired from which the ground truth data base could be built. Construction of the data base was separated into two halves. The first half was acquisition of elevation data which accurately modeled the relief present in the topography of the test site. The second half was construction of a feature map which accurately represented the geometry and radar return (dielectric) properties of the objects and features, natural and man-made, present in the test site. The construction details of making this data base for SLAR validation are discussed in Section 5. These details will not be repeated here.

Within the boundaries of the ground truth data base were several swaths imaged by the APD-10 radar. For verification purposes some of the terrain common to the imagery and data base was used as the SLAR validation base with which radar simulations were produced.

From this large data base, two areas were chosen for validation of the point scattering method and its computer implementation. Figures 9 and 10 illustrate the terrain of interest, with the appropriate dimensions, distances to ground tracks and altitudes included.

2.3 SLAR Simulation Model

Cognizant of the purpose (validation) and scope (one radar system, two data base test sites, two radar flight paths) of the SLAR task, the members of the simulation group adapted the general point scattering model through alterations in the simulation software (without affecting the basic theory). A special simulation computer program was generated for each radar look direction (i.e., the specific flight parameters were incorporated into the program for each swath); a copy of one version is reported in Volume II.¹⁴

The outlined method of validation is a subjective comparison of real (APD-10) and simulated imagery, thus it is understandable that the frequency, polarization, receiver transfer function and image medium should be duplicated (in effect) by the simulated system. Both the real and simulated systems operate at X-band with HH (transmit/receive) polarization. The near range-to-far range power difference correction for both side-looking systems is accomplished by antenna pattern weighting in the vertical dimension by $\sec^2 \theta$, where θ is the incidence angle. The azimuth antenna gain function was set to be a constant, which may be assumed for a very narrow beamwidth, for example the synthetic beamwidth of a focused SAR.

One aspect of the validation process which is of great interest is the shape of resolution cells for the real and simulated imagery. The simulation programs implement the scanning of the data base such that no sidelobe effects are accounted for. Also, the azimuth resolution does not widen with increasing range, which is opposed to the case for the standard real aperture radar. Rather, the simulated radar takes on the appearance,

¹⁴ Martin, R. L., J. L. Abbott, M. McNeil, V. H. Kaupp, and J. C. Holtzman, "Digital Model for Radar Image Simulation and Results," TR 319-8 Remote Sensing Laboratory, The University of Kansas, August, 1976. Included in Appendix I, Vol. II, ETL TR-0118.

and produces imagery that has SAR (Synthetic Aperture Radar) qualities. The resolution cells are rectangular, similar to the synthetic aperture case where the synthetic beamwidth narrows as $1/R$ so that the azimuth resolution does not degrade with range. The contribution of sidelobes, which are a natural consequence of any antenna, whether real or synthetic aperture, are not included as a first order effect in the simulation but may be implemented later. The resolution of the APD-10 radar is 10 feet by 15 feet (azimuth by range, respectively), whereas the simulated radar has 60 feet x 60 feet resolution. Therefore, a great deal of detail may be discerned from the real imagery that will be absent in the simulation. Large areas of homogeneous radar categories should be similar between the two sets of imagery despite resolution discrepancies.

The transfer function of the optical processing of the real radar signal film has not been modeled. The return signal is stored as voltage and phase on signal film and optically processed (focused SAR) to retain the high resolution characteristics. The simulated radar records only power which is the output of the square law detector in the modeled linear receiver. Thus, the magnitude of the video signal is directly proportional to the average return power. The gross radar phenomena are equivalent for the real and simulated systems, e.g., layover, shadow, range compression (slant range mode), and scattering behavior of the terrain.

Signal fading and multipath which are apparent in SAR imagery are also phenomena common to any radar imagery but the extent to which they are visible in imagery depends upon the resolution of the system (governing the amount of averaging) and of course upon the number of scatterers in the resolution cell.

Signal fading has been implemented in the simulation to model the statistical fluctuations of the average return power⁹; however, due to

⁹ Frost, V. S., J. L. Abbott, V. H. Kaupp, J. C. Holtzman, "Derivation of the General Fading Characteristics for Radar Image Synthesis and Analysis," TR-319-29, Remote Sensing Laboratory, The University of Kansas, Sept. 1977.

the number of independent samples averaged, its presence is less noticeable than in the real radar imagery.

The radar platform was modeled as traveling at a uniform velocity and remaining stable throughout the flight (no yaw, pitch and roll problems). The compensation for flight variations in the real imagery is accounted for in-flight, so the comparison should remain valid with the aspects (flight parameters) of the overall problem taken into account. In the two validations being presented, the simulation and real altitudes, near range distances and swath widths have been assured to be equivalent.

The dynamic range and contrast of the real and simulated imagery will appear different because the simulation utilizes a full 20 dB range in which the photographic medium is a linear intensity recorder. The real imagery has a compressed dynamic range so that the field-to-field variation in greytones is not as apparent. Rather than suppressing the information content in the simulations, advantage has been taken of the full linear dynamic range of film so that the discrimination ability of the simulated system can be observed.

The pulsed nature of the simulated signal is implemented through the resolution cell concept. The direct relationship between the range resolution and the pulse width (in time) can be used to show that the pulsed nature of imaging radars had been implemented in the simulation. Previously stated, the operating center frequencies are very close within the X band. The linear FM rate or chirp of the real radar is implemented in effect, also through the resolution cell concept because the range resolution is directly related to the pulse width, and inversely proportional to the RF bandwidth.

As a conclusion to the previous paragraphs about similarity between the radar systems, flight parameters, terrain, and imagery being scrutinized, a good deal of effort has been made to arrange a fair test (subjective though it may be). The major obstacle in the comparison is the difference in resolution between the real and simulated systems. Allowances

must be made for the details which will exist in the real imagery but will be averaged out of the simulated imagery. The next topic of discussion is the choice of empirical microwave reflectivity data for the radar categories within the Pickwick site, upon which the point scattering method depends heavily.

2.4 Microwave Reflectivity Data

The point scattering method of radar simulation relies foremost upon implementation of the greytone equation (5). The term σ^0 (differential scattering cross-section coefficient) appearing in that expression is a key element in the understanding of microwave-terrain interaction, and is intimately related to the frequency and polarization of the measuring system plus the physical state and electromagnetic response of the target scatterer. Upon the specification of frequency and polarization of the simulated system, and as the list of distinct categories within the Pickwick site was being compiled, a search was begun to find curves of σ^0 versus θ (incidence angle) for distinct radar categories within the scene. Two major classes of scatterers were delineated at the outset of this task, distributed and cultural targets.

The distributed targets may be envisioned to be area extensive regions with a specific microwave scattering response. The homogeneous region must be at least as large as the resolution element of the radar (or scatterometer) being modeled, the individual scattering centers located in the cell must be randomly located, and there must be a large number of scattering centers within each resolution cell of the larger homogeneous region. The satisfaction of these criteria allow precise (repeatable) measurements to be made of σ^0 versus θ (assuming the target characteristics are stable) for the distributed target because the return signal consists of the contributions of many independent-phase signals. Just as the data can be gathered (power measurements) and σ^0 versus theta calculated by an expression similar to the radar equation, the reverse is possible. The average return power for

a distributed target can be found through simulation with the aid of σ^0 versus θ data, and with the use of the greytone equation from the point scattering method. The Pickwick site was dissected and analyzed to determine radar return categories, and to determine, for instance, what types of vegetation should be characterized separately by their respective differential scattering cross sections. Empirical data were found in the literature and in the RSL data bank to account for the behavior of the majority of categories.¹¹ Interpolation of empirical σ^0 data was used to derive σ^0 trends for the categories for which measured data does not exist; this does not include cultural targets. The backscatter data employed in the SLAR validation task are presented in Volume II.

Cultural targets, referred to earlier, will be defined within the context of radar simulation to be man-made objects and features. Their radar returns are characterized by the high probability of specular reflection, which is obviously dependent upon the construction geometry, orientation with respect to the radar platform, antenna beamwidth and system resolution. An example of a specular reflector which is not a cultural target is a pond. The fact that radar returns from cultural targets are so highly dependent upon orientation, and the fact that cultural targets do not ordinarily satisfy the criteria of the previous paragraph illustrate that σ^0 data for cultural targets are not ordinarily obtainable nor applicable to digital radar simulation. An alternate means of indicating the existence of a cultural target is a symbolic representation of σ^0 as an isotropic +20 decibels. Thus, for any flight path and data base orientation the cultural target behaves the same. The rationale for this type of treatment is probabilistic estimation of the cultural target return strength, based on the knowledge of the types and orientation of a majority of the corner reflectors, boathouses, homes, and various other structures in the SLAR validation strips of the ground truth data base. Hypothetically speaking,

¹¹ Abbott, J. L., R. L. Martin, M. McNeil, V. H. Kaupp, and J. C. Holtzman, "Backscatter Data for the Digital Radar Image Simulation of the Pickwick, Alabama Site," TR 319-7, Remote Sensing Laboratory, The University of Kansas, February, 1977. Included in Appendix G, Vol. II, ETL TR-0118.

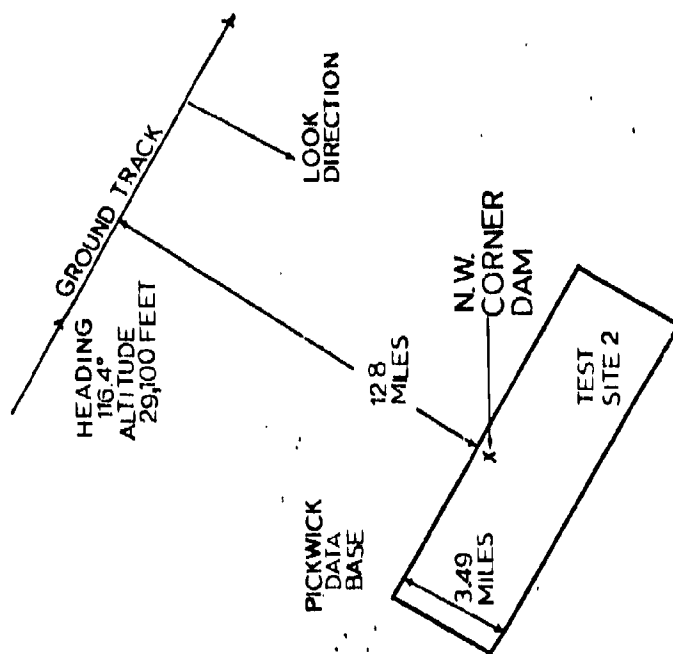


Figure 10.

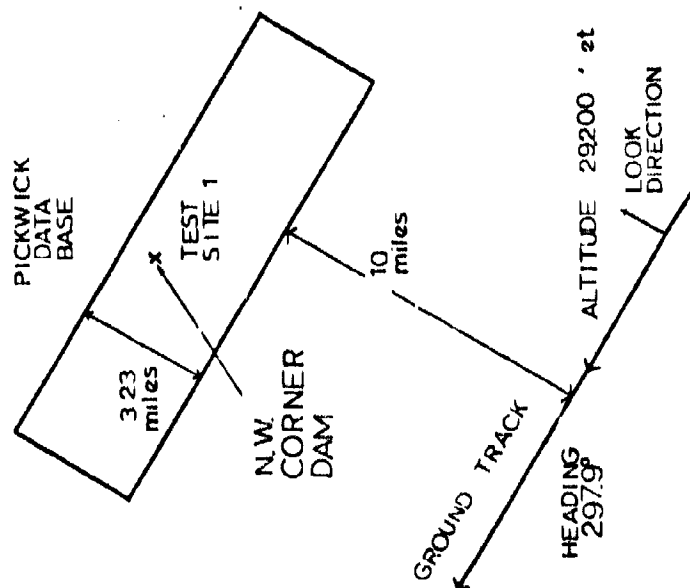


Figure 9.

as the density of cultural targets increases, one would normally expect a higher probability of specular reflection (backscatter direction), and in effect, this is exactly the result of implementing cultural target average return power as a spatially isotropic constant value.

2.5 SLAR Validation Scenes

Once the validation terrain site had been selected, the ground truth data base produced, the radar system operating parameters specified, the catalogue of empirical σ^0 data formed, and the software implementation refined, simulation of radar imagery for two sites was begun.

The sequence of events in the formation of simulated images includes: (1) Input radar system and flight parameters, e.g., operating frequency, polarization, resolution cell size, flight altitude, ground track location, flight heading, etc.; (2) Input the ground truth data base, a rectangular matrix symbolically representing elevation and backscatter properties; (3) Run the computer programs. Important computations within the body of the program form data such as local slopes, resolution cell areas, local angle of incidence, radar angle of incidence, range to resolution cells. These intermediate results are used with the microwave reflectivity data, σ^0 , to compute the average fraction of power backscattered to the antenna. The formation of greytone for each resolution cell in the image is the final step, and these values are stored on magnetic tape and then displayed.

The computer programs which comprise the simulation package are discussed in some detail in Volume II,¹⁴ where a copy of one version of the package is available.

2.6 Results

Preliminary validation studies were performed on the SLAR model and implemented.¹⁴ Those investigations were made with a geometric data

¹⁴ Martin, R. L., J. L. Abbott, M. McNeil, V. H. Kaupp, and J. C. Holtzman, "Digital Model for Radar Image Simulation and Results," TR 319-8 Remote Sensing Laboratory, The University of Kansas, August, 1976, Included in Appendix I, Vol. II, ETL TR-0118.

base, that is, a computer generated site of three dimensional, deterministic objects. The very specific purpose of the tests were to judge the accuracy of geometrical/propagation phenomena, i.e., radar shadow and layover. The type of validation performed was quantitative, as opposed to the subjective reporting here, because with known radar and flight parameters, and a deterministic ground truth data base, the lengths of shadows and distances of layover can be calculated. The results of the initial SLAR studies using the geometric data base indicated that the simulation package very accurately implemented these types of phenomena with good success. The quantitative aspect of the validation studies are reported in Volume II and, in addition, the simulation software are discussed.¹⁴

The more difficult task of subjective validation is now at hand. It is appropriate to question what the results of this comparison actually infer about the point scattering method, the many assumptions associated with making feasible the software implementation, and the assumptions about the resolutions of the real and simulated imagery. This test will reflect the validity of many simplifications and assumptions, for instance: (1) Parameters and transfer function of the real radar and its associated optical processing; (2) Parameters and transfer function of the simulated radar; (3) Validity of the empirical differential backscatter cross-section coefficient data; (4) Accuracy of the ground truth data base (elevation, planimetry, radar categories) and the source material from which it was constructed; (5) Software implementation of the general point scattering model; (6) Validity of the point scattering model; and (7) Comparison of high resolution images with less detailed simulated images. Though these assumptions are simplistic, they are necessary for physical realizability of the test. However, the verification of a model lies in its ability to faithfully predict the real-world phenomena, not in how faithfully each and every subcomponent of the phenomena is reproduced. This is obvious because the implementation of a model may, for instance, compute intermediate data out of the chronological order of the actual phenomena, without becoming invalid.

¹⁴ Martin, R. L., J. L. Abbott, M. McNeill, V. H. Kaupp, and J. C. Holtzman, "Digital Model for Radar Image Simulation and Results," TR 319-8 Remote Sensing Laboratory, The University of Kansas, August, 1976. Included in Appendix I, Vol. II, ETL TR-0118.

The next major difficulty which arises is what are appropriate features of simulated imagery by which its "quality" can be judged? Four criteria which may serve as starting points in this analysis will be the similarity of shadow, graytone and texture between the real and simulated images, and the geometrical fidelity of the simulation. This list is intentionally incomplete because one wisely would avoid putting words in the mouths of more experienced image interpreters.

Figure 11 is a side-by-side comparison of a real image and a simulated image for the 297.9° heading (true magnetic north), 29,200 foot altitude (above mean sea level), with an X-band, HH radar. The image is the upper strip map, and the look direction (same for both images) is indicated by an arrow. The swath width represents 3.23 statute miles, with the distance between the near range and ground track being 10.0 statute miles. The resolution of this real image is 10 feet x 15 feet and for the simulated image it is 60 feet x 60 feet. These images correspond to the flight and test site situation of Figure 9. Several prominent features are identified on the real image for validation purposes.

The greatest microwave return in the real image is from "cultural" targets such as the dam, boathouses, locks, and an industrial complex. Cultural features compare well on the basis of graytone and location between the real and simulated images. In addition, multipath from the water increases the return from the far shore, defined as the land masses preceded by water as viewed from the perspective of the radar platform. This multipath effect is often referred to as "far shore brightening".

The textural quality of the simulation is quite comparable to that of the real image. For instance, the texture of the cultivated lowlands, which is in part due to the actual smoothness of the vegetation canopy, and in part due to the averaging of fading in this category, is favorably compared to texture in the real image. The deciduous trees of the lowlands and highlands have been assigned heights according to a Gaussian distribution in the simulation for the purpose of realistically modeling the actual

growth pattern.¹⁵ The effect of the normal distribution with its associated mean and standard deviation is to increase the variability of greytone within forested regions, thus making the simulated images very similar to the real images.

Judging the simulation on the basis of greytones in distributed target regions, there is seen to be a great deal of agreement overall between the images with two exceptions. The low greytone (dark) crop of the lower left hand corner of the simulation, was modeled as corn. The discrepancy can be accounted for by the misrepresentation of the radar category in the ground truth data base. The source material for categories was aerial photography, thus this error can be traced to interpretation of the vegetation in this region. Close scrutiny of the golf course shows that it is too dark, but for another reason. Between adjacent fairways the deciduous trees are not apparent in the simulation. This is caused by the averaging of the backscatter properties of the smooth short grass and the deciduous trees. Since the resolution cells are larger than the width of the stands of trees, their normally high return is not visible.

The geometric fidelity of the simulation is good. The locations and elevations of prominent features such as the river, dam, reservoir, inlets, islands, settling ponds, and hills (which in turn governs the lengths of shadows and amount of layover) are observed to be accurate. The best area for comparison of shadow is in the forested highlands.

Figure 12 is a side-by-side comparison of a real radar image and a simulated image for a heading of 116° (true magnetic north), 29,100 foot altitude (above mean sea level), with an X-band, HH radar. Again, the real image is the upper strip-map. The swath-width is 3.49 miles, with the near range to ground track distances being 12.8 miles. Resolution of the real image is 10 feet x 15 feet and of the simulated image is 60 feet by 60 feet. These images correspond to the flight and test site situation of Figure 10.

¹⁵ Abbott, J. L., V. H. Kaupp, J. C. Holtzman, "Medium Resolution Radar Image Simulation of Deciduous Forests: A Study of Candidate Techniques," TR 319-9, Remote Sensing Laboratory, The University of Kansas, August, 1977. Included in Appendix H, Vol. II, ETL TR-0118.



SAR IMAGE

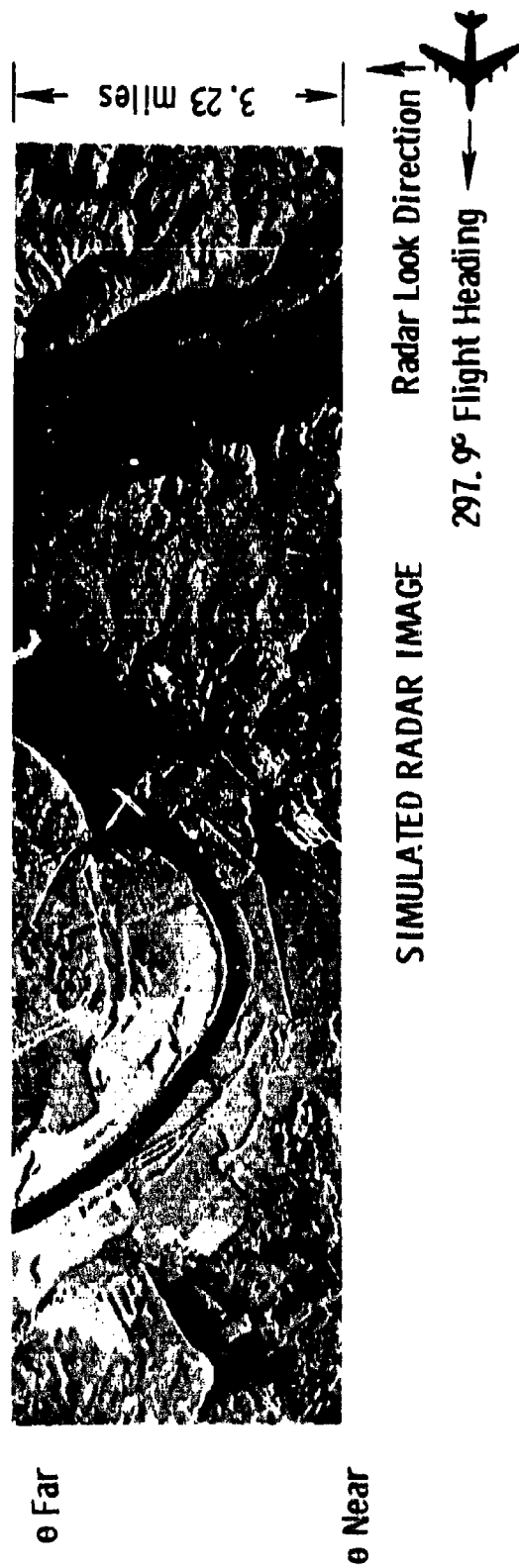
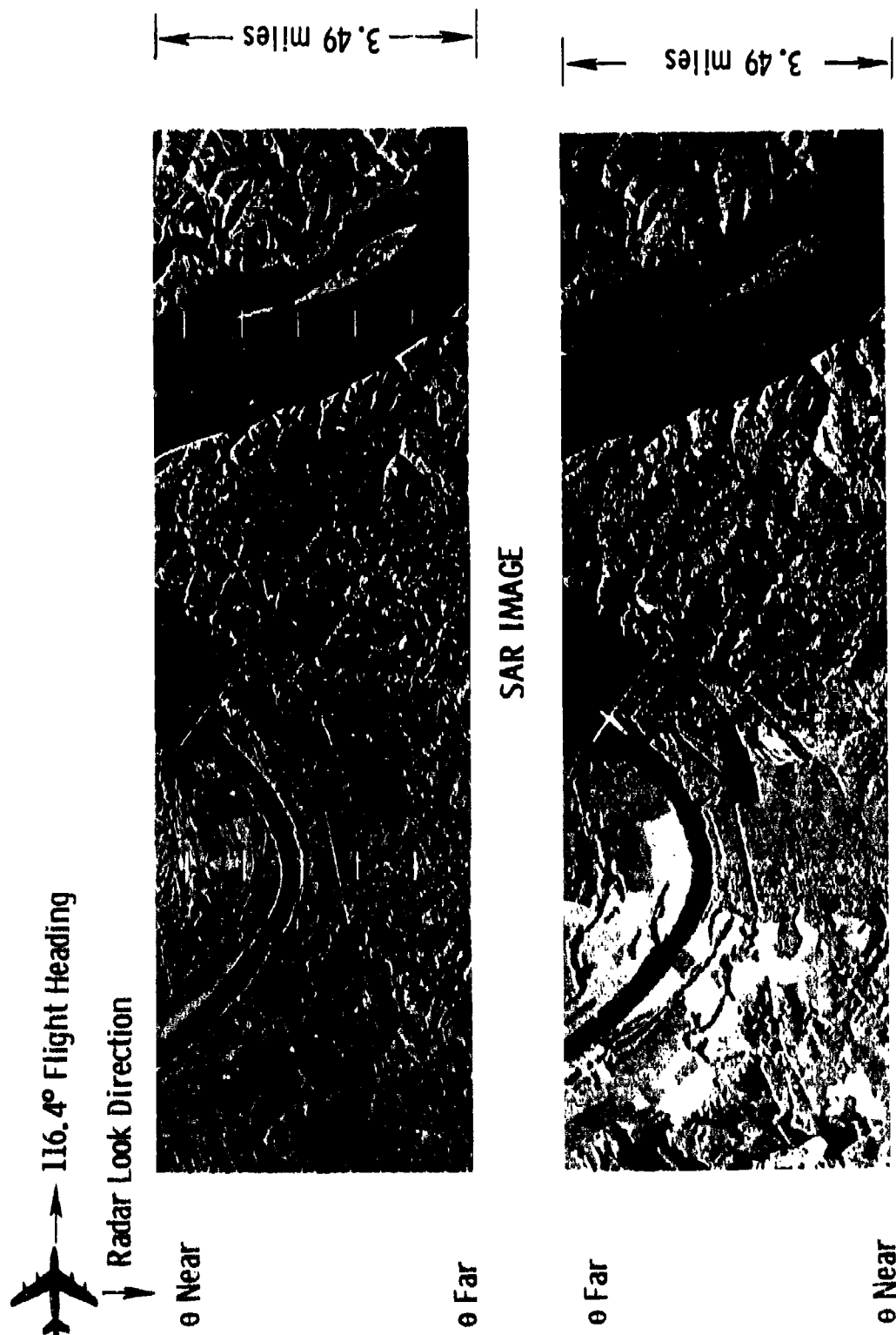


Figure 11. Simulated Radar Image Compared to SAR Image of Pickwick Data Site: 297.9° Magnetic Flight Heading



SIMULATED RADAR IMAGE

Figure 12. Simulated Radar Image Compared to SAR Image of Pickwick Data Site: 116.4° Magnetic Flight Heading

Comparing first the accuracy of the modeling of cultural targets, the dam, locks, and boathouses are well represented. However, the industrial complex located near the settling ponds does not have a composite of orientations, or construction geometry and materials to give a high level of return, as indicated in the upper strip map. Since cultural targets are represented in backscatter response by a spatially isotropic +20 dB, they are white (greylevel 255) in the simulation. Several cultural targets located in the inlets were not specified in the ground truth data base, therefore they are absent in the simulation.

A textural comparison again is favorable for most of the terrain; the cultivated lowlands are basically smooth whereas the areas covered by deciduous trees have a rougher texture. Note however, that the tree-covered region around the settling ponds are darker and smoother than the simulation indicates. This discrepancy is caused by the fact that the behavior of trees was modeled for deciduous varieties only. The trees in the vicinity of the settling ponds have since been discovered to be conifers, most of which were planted within one season. Inspection of real radar imagery of alternate sites has shown the smooth texture and relatively low return (as compared to deciduous tree return) to be characteristic of coniferous forests.¹⁶

An evaluation of geometric fidelity would again lead to the conclusion that elevations, locations, and boundaries compare well between the two images, keeping in mind the resolution discrepancies.

Greytone comparisons, on the other hand, show an amount of dissimilarity between the cultivated lowlands of the two strip maps. Recalling that the images are displayed with widely differing dynamic range, it is natural that field-to-field greytone variations will appear large in the simulated version. However, a field that is dark with respect to its neighbor will be so no matter what the dynamic range of display greytone, within reason. There are several vegetated regions to the left of the

¹⁶ Hardy, N. E., "Examination and Analysis of Vegetation Boundary Zones Using Aerial and Orbital Data Sources", PhD. Thesis, The University of Kansas, 1976.

river bend which are too light with respect to deciduous trees, thus indicating a false identification of category, or a bias in the backscatter response of the sigma zero curve used for those regions. The true physical state of the crop in these regions might, for instance, be dry in comparison to the same crop from which σ^0 data were collected, accounting for the relatively low grey level of vegetation in the real radar image. Seasonal changes in backscatter response¹⁷, rather than crop misidentification are suspected to be the leading source of grey-tone comparison errors. The grey level comparison of the golf course shows the deciduous trees between fairways have again been swallowed due to the resolution and to the very low return of smooth grass.

2.7 Conclusions

A brief subjective analysis of two simulated images has been performed. The painstaking effort which has gone into the construction of a ground truth data base for radar image simulation is in evidence. The simulated images, though judged to be of good quality on the basis of geometric fidelity, texture and grey level, have shown that there are improvements and advances to be made in the science of radar simulation. For example, grey level discrepancies, which are not due to the dynamic range of presentation, illustrate that a study of seasonal changes may be in order.

Each test site from the Pickwick data base has been calculated to contain approximately 2.6 million data points, each containing elevation and dielectric information. It is no trivial task to simulate radar images for expanses of terrain such as these, and it is surprising to have end products which are this fine. With all due modesty, the qualitative

¹⁷ Bush, T. F., et al., "Seasonal Variations of the Microwave Scattering Properties of the Deciduous Trees as Measured in the 1-18 GHz Spectral Range," RSL TR 177-60, The University of Kansas.

validation of the point scattering method and its digital implementation are believed successful. This verification lends credence to the idea that the point scattering model and the software implementation are not the sources of discrepancies between the real and simulated images, but rather, that a more extensive catalogue of empirical σ^0 data (with season as an additional parameter) should be sought.

3.0 PPI SIMULATION AND VALIDATION

This section describes the results of the work performed to validate the point scattering radar image simulation model for Plan Position Indicator (PPI) radar applications.

Three subareas of the Pickwick test site were simulated using the PPI model. Each of these areas was simulated twice in order to produce results with different look directions. Therefore, six simulations will be presented and discussed in this section. The same simulation parameters were used in each of these simulations (except for slight variations in the near range distance and the altitude which were changed to match the parameters of the original comparison images). In essence, the scope of this validation work has been limited to one data base (from which selected subareas were extracted), one radar simulation model (PPI), and one radar system. In addition, though, simulations of the same scene with different look directions were produced to analyze the effect of the look direction on the simulation output images.

The validation process used for this model has been a qualitative, subjective one. The intent was to compare simulated images to other radar images and analyze similarities and differences. Optimally the reference images would be real PPI imagery of the test site. Unfortunately we were unable to locate, and ETL could not provide us with, actual PPI images for the scene. Another task performed at RSL and reported (Section 2.0) in this document is validation of the Side-Looking Airborne Radar (SLAR) model. Real SLAR images of the test site were available for direct comparison in the validation of the SLAR model. The simulated SLAR images were chosen for the reference imagery in the validation process for PPI. If the results produced by the SLAR model could be validated by direct comparison to the real images and the simulated PPI imagery compared well with the SLAR images, one could assume by inference that the PPI model implementation was also valid.

This method of validation (comparison to simulated SLAR images) dictated a number of decisions in the implementation of the PPI simulation model. The radar system modeled in this study was a hypothetical

PPI system with perfect characteristics. The antenna pattern was modeled without sidelobes, the transmitted pulse as a perfect pulse, the receiver as perfectly linear with a constant of one ($M=1$), and the recording medium (film) as linear across its range. These assumptions may not appear reasonable for modeling a real radar system. However, the purpose was not to model a specific real radar but to validate the point scattering radar image simulation model for general PPI applications. To attempt to model realistic system deficiencies when imagery was not available from any real PPI system would have been quite arbitrary, in itself. We chose to produce the best possible simulations we could within the normal limitations imposed by data base and radar return data, for the purpose of validation. This was done by simulating each element of the radar system (antenna, transmitter, receiver, recording medium) as a perfectly functioning unit. These same assumptions were made in the SLAR model implementation whose results served as the reference baseline for comparison to the PPI results. Therefore, differences between the outputs can be attributed directly to the model implementations. Had system deficiencies had been included in the models, it would have been difficult, if not impossible, to separate the differences resulting from the basic models themselves and those as the result of the real system limitations that were modeled.

It should be emphasized, however, that the model, itself, is completely general and capable of modeling non-linearities and distortions within a real operating system if they are properly described. It is not easy to provide a strict mathematical description of such system deficiencies and implementing them in the computer software implementation of the model may be very costly in terms of execution time.

Other parameters in the simulation model were also chosen to optimize the comparison to the simulated SLAR results. As a result the simulated images included at the end of this section do not resemble typical PPI imagery. The most immediate difference is in the display format. These simulated images do not have the characteristic "pie-shaped" form

that is produced when a PPI radar system images a 90° sector (45° either side of the line of flight) from zero degrees incidence to near grazing. The simulated SLAR images represented a rather narrow range of radar incident angle (approximately 60° to 70°). Therefore, no imagery were available for comparing the results of the PPI simulation at lower incident angles and so we did not simulate that portion of the data base with the PPI model, either, thereby reducing the total cost for the performance of this task and minimizing possible confusion caused by simulating an angular range not comparable to the SLAR images.

The narrow range of simulated images in the azimuth direction is the result of the fundamental difference between the SLAR and PPI models. In operation, a SLAR system sends a pulse out at right angles to the direction of flight. The antenna is stationary relative to the aircraft. The movement of the aircraft provides the motion of the antenna in the azimuth direction. This allows the model to process the data in rectangular coordinates since the look direction of the radar is always parallel to the rows of the data base. In a PPI system, which is a forward-looking radar, the antenna is scanned from left to right to provide imaging capabilities in the azimuth direction. Except for the scan line directly along the line of flight, the look direction for the radar is not parallel to information in the data base, which is stored in rectangular coordinates. To overcome this problem in the PPI model, the data base is transformed into polar coordinates which more closely reflects the operation of a PPI radar system. The effect of this difference is that SLAR and PPI images are directly comparable only along one scan line, the one scan line along the line of flight for the PPI. For all other scan lines the look direction of the two systems are no longer exactly the same. The farther the scan is from the line of flight in the PPI model, the more it varies from the SLAR model. To minimize this difference, only very narrow (in the azimuth direction) simulations were produced. Since the position of the radar platform was far from the data base (approximately 60,000 feet), the scan lines for the PPI simulation were very nearly parallel to the rectangular data base for a narrow

range. Small sections of the data base were selected and, thus, the resultant small PPI images are very close to having the same look direction as the SLAR. Because the areas simulated were quite small, three different subareas from the data base were simulated to have results from a wide variety of ground scene profiles.

Real PPI radar systems are typically used for terrain avoidance and locating cultural targets ahead of the aircraft. The system parameters such as gain and bias are optimized for these targets. Furthermore a slow-decaying phosphor screen with only four to ten distinct levels form the display medium. These factors combine to produce "black and white" images with considerably less terrain detail than found in medium resolution SLAR imagery. These parameters in the PPI model were set to produce imagery more comparable to SLAR imagery for purposes of validation. This choice of parameters has no effect on the basic PPI model itself; they are only input parameters to the computer program. The scenes could have been formed with the conventional greytone display, but, obviously, the SLAR comparison capability would have been lost.

The assumptions that were made in the simulation model described above emphasize the generality and utility of the model, not limits for its application. The model was able to be used for the specific purpose of PPI validation against SLAR imagery. If other applications are desired (such as modeling a real PPI system) the model is easily adapted to that function.

3.1 Work Plan

There were four essential ingredients required for the production of the simulated PPI images. They were:

- (1) A ground truth data base describing the planimetry of the test site.
- (2) Digital elevation data for the test site.
- (3) Differential scattering cross-section (σ^0) data for the various scattering types included in the chosen test site.
- (4) A digital computer program to implement the point scattering radar image simulation model for PPI.

The personnel and resources at RSL were assigned various activities so that the above tasks could be performed in parallel as much as possible. The first major step was choice of an appropriate test site. In order to minimize duplication of effort, a single test site was chosen for use in the performance of multiple tasks for this contract. Since the scene was to be used for validation of radar models, it was important that the test site contain a wide range of features and effects found in real radar imagery. It was necessary that appropriate data sources be available to provide the input data described above for the models (planimetry, elevation, and σ^0) for the selected area. In addition, for the validation, at least real SLAR images had to be available for the area. (No areas were located that satisfied these criteria for which real PPI imagery were available). An area centered around the Pickwick Dam in Tennessee was chosen that fulfilled the above requirements except for complete availability of empirical backscatter (σ^0) data. For those targets in the test areas for which σ^0 data could not be located, solutions were reached¹¹ by combining theory, literature and intuition.

A data base of the Pickwick test site had been constructed previously at RSL for other applications. The resolution of this data base was approximately one hundred feet and therefore not sufficiently detailed for simulation of PPI at the desired resolution. This data base was refined¹³ to provide an approximate resolution of sixty feet which was adequate for this application (Section 5.).

Digital elevation tapes of the Pickwick site were provided by ETL. Personnel at RSL were responsible for collecting the necessary data from multiple magnetic tapes and reformatting them to conform to program inputs.

When the two portions of the data base had been completed (ground cover data and elevation data) the two outputs were combined to produce

¹¹ Abbott, J. L., R. L. Martin, M. McNeill, V. H. Kaupp, and J. C. Holtzman, "Backscatter Data for the Digital Radar Image Simulation of the Pickwick, Alabama Site," TR 319-7, Remote Sensing Laboratory, The University of Kansas, February, 1977. Included in Appendix G, Vol. II, ETL TR-0118.

¹³ Komp, E., J. L. Abbott, V. H. Kaupp, J. C. Holtzman, "Improved Resolution Digital Ground Truth Data Base: Pickwick Site," TR 319-23, Remote Sensing Laboratory, The University of Kansas, August, 1977.

a single data matrix containing the necessary information for simulation input.

While the data base formation was in progress, the various back-scatter return categories included in the data base were identified and the necessary empirical σ^0 data were collected from various sources. For those categories for which σ^0 data could not be located, combinations of theoretical studies and empirical data from similar categories were utilized.

The computer program to model the PPI radar systems was written and tested as construction of the data base was in progress. When the final data base was complete, selected subsections were input to the PPI simulation program to produce the images presented in this section. While the PPI model implementation was being developed, a computer package to produce SLAR simulations was written independently.

When both sets of simulated images were available, a critical comparison of the two results was made. The results of this comparison is presented in subsection 3.6.

3.2 Data Base for Simulations

The data base input requirement for the PPI simulation model is a polar coordinate digital matrix representing the ground scene content. The information necessary was recorded in two data values for each point in the matrix (representing a finite area of the real ground scene). These two pieces of information are (1) elevation variations for the area, and (2) a category assignment describing the microwave reflectivity characteristics of the area. The construction of this data base in a rectangular coordinate system is discussed in Section 5. The content of this data base is transformed into a matrix in polar coordinates by program software. Because of the particular approach selected for transformation to polar coordinates, it is necessary that the size of area represented by the points in the rectangular data matrix be significantly smaller than the size of the resolution cell of the radar system being modeled.

The same rectangular data matrix used for simulation of SLAR images was used for this PPI task. It was converted into polar coordinates for

simulation of PPI images. For the purpose of validating the PPI model against the results of the SLAR model, having the same data base as the input to the two simulation models (albeit converted to polar coordinates for PPI) was especially useful. The input data base used to produce the PPI simulations was subset of the data base of the Pickwick test site used for the SLAR validation task. It is described fully in Section 5. of this document. Three subsets of the original SLAR data base were chosen for the work with the PPI model. Each specified area was extracted and rotated to match the flight line of the APD-10 original imagery. The rotation was required to align the data base orthogonal to the line of flight of the aircraft. Three different areas were chosen because the SLAR and PPI results are comparable only over a narrow range in the azimuth direction of the PPI image. Different look directions for each of these three areas were produced.

3.3 PPI Simulation Model

The point scattering radar image simulation model provides a closed system model of radar operation. The details of its implementation in computer software together with a theoretical development of the model is presented in Volume II.¹⁸

The following paragraphs will provide a brief summary of the implementation and a description of the system parameters used in this particular application.

Conceptually, the PPI simulation program organizes the information in the data base into cells representing resolution cell size areas for the radar being modeled. The return power from each of these areas is computed independently and converted to a relative greytone and output for display on an appropriate medium.

The first step in the simulation process is to group the information of the input data base into resolution cell size areas. This is a significant problem for the PPI model for two reasons. First the dimensions

¹⁸

Komp, E., V. H. Kaupp, J. C. Holtzman, "Digital PPI Model for Radar Image Simulation and Results," TR 319-19, Remote Sensing Laboratory, The University of Kansas, August, 1977, Included in Appendix J, Vol. II, ETL TR-0118.

of the resolution cell change radically over the wide range of incident angles. Typically PPI radar systems image from approximately under the platform ($\sim 10^\circ$ incidence) to near grazing angles in the far range. The size and shape of the resolution cell changes from relatively narrow in the azimuth direction and wide in the range dimension at near range to wide in the azimuth direction but very narrow in the range dimension at far range. The second complication is the result of the changing look direction of the system with respect to a fixed point on the ground as the antenna rotates in the azimuth direction. The look direction is important for calculating areas of shadow and the local effective incident angle. Neither of these problems can be easily or accurately handled in rectangular coordinates, the coordinate system in which the input data base was constructed. The geometry of a polar coordinate input data base is transformed into a data base of resolution cells represented in polar coordinates.

The next step is to calculate the return power from each of these resolution cell areas. For medium resolution radar systems, such as the sixty foot resolution system simulated for the performance of this task, these areas can be simulated as independent samples. The simplification allowed by ignoring the effect of adjacent cells greatly reduces the computational complexity of the problem. The information of adjacent cells is needed only to calculate the local slopes of each cell and to calculate the effects of radar shadow. At each cell the local incident angle is calculated from the radar incident angle and the local terrain slope at the cell. The category information stored at each cell describes the backscatter target type represented by the area. By use of a curve fit to empirical backscatter data for that category, a σ° value for the specific angle of incidence is calculated. This information is used to calculate the return power from the resolution cell area by application of the general radar simulation model.

The final step is to produce an output image. The array of return powers calculated in the previous step is converted to a relative greytone representing a film density on photographic film. Each greytone value

represents the return from a specific resolution cell area on the ground. At this point, this information is still in a polar coordinate system. Another transformation is made from polar coordinates to rectangular coordinates and a digital matrix of graytone values is produced. This result can be transferred to any appropriate display device such as IDECS* or DICOMED+ to produce a visual output of the simulated image.

3.4 Terrain Return Data

After specification of the operating parameters (frequency and polarization) of the real PPI radar and after identification of each different category of radar scatterer located in the proposed scene to be simulated, it was necessary to obtain appropriate terrain return data. The different categories of radar scatterers identified in the Pickwick reference scene test site were separated into two major classes: 1) distributed targets, and 2) cultural targets.

Distributed targets are homogeneous regions of specific microwave scattering categories. Each homogeneous region must be at least as large as the resolution element of the radar being modeled, the individual scattering centers located in a resolution cell must be randomly located, and there must be a large number of scattering centers in each resolution cell within a homogeneous region. When these conditions are satisfied, an average value of the scattering cross-section (σ°) can be used to model the radar return from these homogeneous areas of terrain (distributed targets). Most of the terrain located in the reference scene data base of the Pickwick site satisfied these criteria. Thus, differential scattering cross-section data (σ°) were used to model the radar return properties of the terrain in the PPI images formed from the Pickwick data base. Actually, empirical σ° data were used (as opposed to theoretical), for distributed targets.

* Acronym meaning Image Discrimination, Enhancement, Combination, and Sampling, the name given to the image processing station located at RSL.

+ DICOMED is the name of the company which manufactured one visual display system, located at ETL.

These data were obtained from the literature and from the RSL data bank¹¹. The best match that could be found between available empirical σ^0 data and the identified distributed targets in the Pickwick site was sought. The empirical σ^0 data were not taken from radar imagery of the Pickwick site or any other site. The details of what σ^0 data were used to form PPI images are presented in Volume II¹¹.

Cultural targets are here defined to be manmade objects and features. Their radar returns are characterized by specular reflection. They cannot be modeled as distributed targets. To model cultural targets by digital computer is exceptionally complex requiring tremendous detail about each such target to be included in the data base. An evaluation was made of the kinds of cultural targets present in the Pickwick site, their orientations, and the number of them. It was concluded that symbolic modeling of these targets would be a reasonable approach. By symbolic modeling is meant that the location of each cultural target was pinpointed in the data base but the orientation, size, geometry, etc., was not. Cultural targets were assumed, for the purposes of PPI image simulation, to be isotropic radiators having an effective differential scattering cross-section of +20 dB.

This approach certainly is not an accurate model. In these simulations all cultural targets then produce the maximum grey level, 255 in these instances. In real imagery a cultural target will return sufficient power to saturate the film density only if its orientation relative to the radar system is appropriate. In most all cases, however, the return is quite high relative to surrounding distributed targets. Furthermore, when the data base was constructed, the intent was to develop a general omnidirectional data base, not one specifically intended for a single look direction or radar system. For these reasons this approximation was considered acceptable for this task, especially in an area such

¹¹ Abbott, J. L., R. L. Martin, M. McNeil, V. H. Kaupp, and J. C. Holtzman, "Backscatter Data for the Digital Radar Image Simulation of the Pickwick, Alabama Site," RSL TR 319-7, University of Kansas Center for Research, Inc., Remote Sensing Laboratory, Lawrence, February, 1977. Included in Appendix G, Vol. II, ETL TR-0118.

as this where the proportion of cultural targets to distributed targets was very small.

3.5 Simulated Radar Image Formation

Only after all of the major subtasks described in section 3.1 had been properly completed could production of the final output images begin. Those subtasks were 1) creation of digital data matrix; 2) collection of backscatter (σ^0) data for the distributed targets in the test site; and 3) development and testing of computer software.

The results of the first two tasks (data base and σ^0 data) were used as input to the PPI radar simulation computer program. One other section of input data to describe the radar platform position and the radar system parameters was required before execution of the program. These parameters were chosen to match the operating parameters used in the SLAR simulation wherever possible to facilitate the comparison of the two outputs during validation. The most significant difference in system characteristics between the PPI model and the SLAR model as implemented for this validation study was in the antenna pattern function. The SLAR model used a $\sec^2\theta$ model for the antenna pattern, while the PPI model used a $\sec^2\theta \csc\theta$ function which was selected for the work in Section 4 (also a PPI). Over the very narrow angular range for which the PPI images were formed, this represented, at most, a bias difference when compared to the SLAR results.

There were essentially two sets of parameters used to produce the six PPI simulations. One set of parameters was used to produce the simulations of the three areas in which the look direction corresponded to the look direction of the SLAR model for the 116° flight heading. For these simulations the look direction is approximately northeast to southwest. For these simulations the PPI radar platform was assumed to be positioned exactly on the flight line of the SLAR for the 116° heading, and the PPI look direction at right angles to that line of flight for the SLAR. The other parameters were chosen to simulate sixty foot resolution in the image scene area, which corresponded to the resolution of the

SLAR model. A list of these parameters is included in Table 2. A slightly different set of parameters was used to produce the simulations of the three test sites from the other look direction. For these simulations the look direction is approximately southwest to northeast. For these simulations the PPI radar platform was positioned on the flight line of the SLAR for the 297° heading. These changes reflect the difference in the aircraft altitude and near range distance to the target site. These parameters are summarized in Table 3.

3.6 Results and Validation

The validation of the PPI model was somewhat complicated because real PPI images of the test site were not available. At the time of contract negotiations both the contracting officers at ETL and the members of the Kansas Simulation Group recognized this lack of comparison PPI imagery. At that time both parties agreed to perform the validation of the PPI model implementation by comparison to the results of the SLAR simulation model. Within the existing time frame it was not feasible to choose an additional target scene for which PPI imagery were available and to produce another data base for simulation purposes. In spite of these deficiencies we found validation of the PPI model at the Pickwick site a necessary task because of its impact on the work to be performed in the area of remote guidance which is reported in Section 4 of this document. It is fully recognized that results reported in this section do not provide a full and comprehensive validation of the point scattering radar simulation model for PPI applications, but, unfortunately, a more substantive test of the model could not be conducted because of the lack of real PPI radar imagery.

This approach to validation depended heavily on the successful validation of the SLAR simulation output. The results of the SLAR validation are fully documented in section 2.5 of this report and are, in fact, excellent. There are differences between the real imagery and simulated SLAR results, but from a global viewpoint the simulated images compare very favorably. Only with the successful completion of that task were we able

TABLE 2.

PPI Parameters for 116° Flight Heading

Transmitted frequency	X-band
Polarization	HH
Pulse Width	.122 μ sec
Effective Antenna Beamwidth*	.000755 radians
Near Range Distance	68,500 feet
Altitude	29,100 feet
Antenna Pattern	$\sec^2\theta \csc\theta$

TABLE 3.

PPI Parameters for 297° Flight Heading

Transmitted frequency	X-band
Polarization	HH
Pulse Width	.122 μ sec
Effective Antenna Beamwidth*	.00095 radians
Near Range Distance	55,500 feet
Altitude	29,200 feet
Antenna Pattern	$\sec^2\theta \csc\theta$

*Note: The effective antenna beamwidth was changed for the different sets of simulations in order to approximate 60 foot resolution in both image sets.

to confidently proceed with the validation of the PPI model against the results of the SLAR model.

Since there were no real PPI imagery available, and therefore no specific real system to model, we chose to model a hypothetical perfect PPI radar system without real-world limitations. In addition, the choice of system parameters was made to correspond to those used in the SLAR model as closely as possible. Because of the different mode of operation for SLAR and PPI radar systems the images are comparable only over a narrow range. In a SLAR system the antenna is fixed and the look direction of the radar is constant. The system images a swath of ground parallel to the flight path of the aircraft as it moves along. PPI systems on the other hand image in front of the aircraft and the antenna must rotate (usually 90°) to provide imaging capabilities in the azimuth direction. Only that portion of a typical PPI image which would be comparable to the SLAR image was simulated. Figure 13 displays the portion of a normal PPI image that was actually simulated. The look direction for a PPI radar proceeds radially from the radar platform. Simulating a wider area with the PPI model would have complicated the comparison to the simulated SLAR images because of the differences introduced by differing look directions.

Since both the PPI and SLAR implementations modeled ideal systems and the system parameters for PPI were chosen to match those for SLAR, one would expect the images to be nearly identical over the narrow range of comparison. The two sets of results are, in fact, very similar as can be seen in the photographs presented in Figures 14 and 15 where the PPI images are placed adjacent to the portion of the SLAR output to which they correspond. It should be emphasized, however, that the two programs are completely different and independent. The computer implementations of the SLAR and PPI models are listed in Volume II^{14,18}. There are many operational differences but, more importantly, there exists a fundamental difference in the radar data bases used in the two programs. The SLAR model represents the resolution cells on the ground as rectangular

¹⁴ Martin, R. L., J. L. Abbott, M. McNeil, V. H. Kaupp, and J. C. Holtzman, "Digital Model for Radar Image Simulation and Results," TR 319-8 Remote Sensing Laboratory, The University of Kansas, August, 1976. Included in Appendix I, Vol. II, ETL TR-0118.

¹⁸ Komp, E., V. H. Kaupp, J. C. Holtzman, "Digital PPI Model for Radar Image Simulation and Results," TR 319-19, Remote Sensing Laboratory, The University of Kansas, August, 1977, Included in Appendix J, Vol. II, ETL TR-0118.

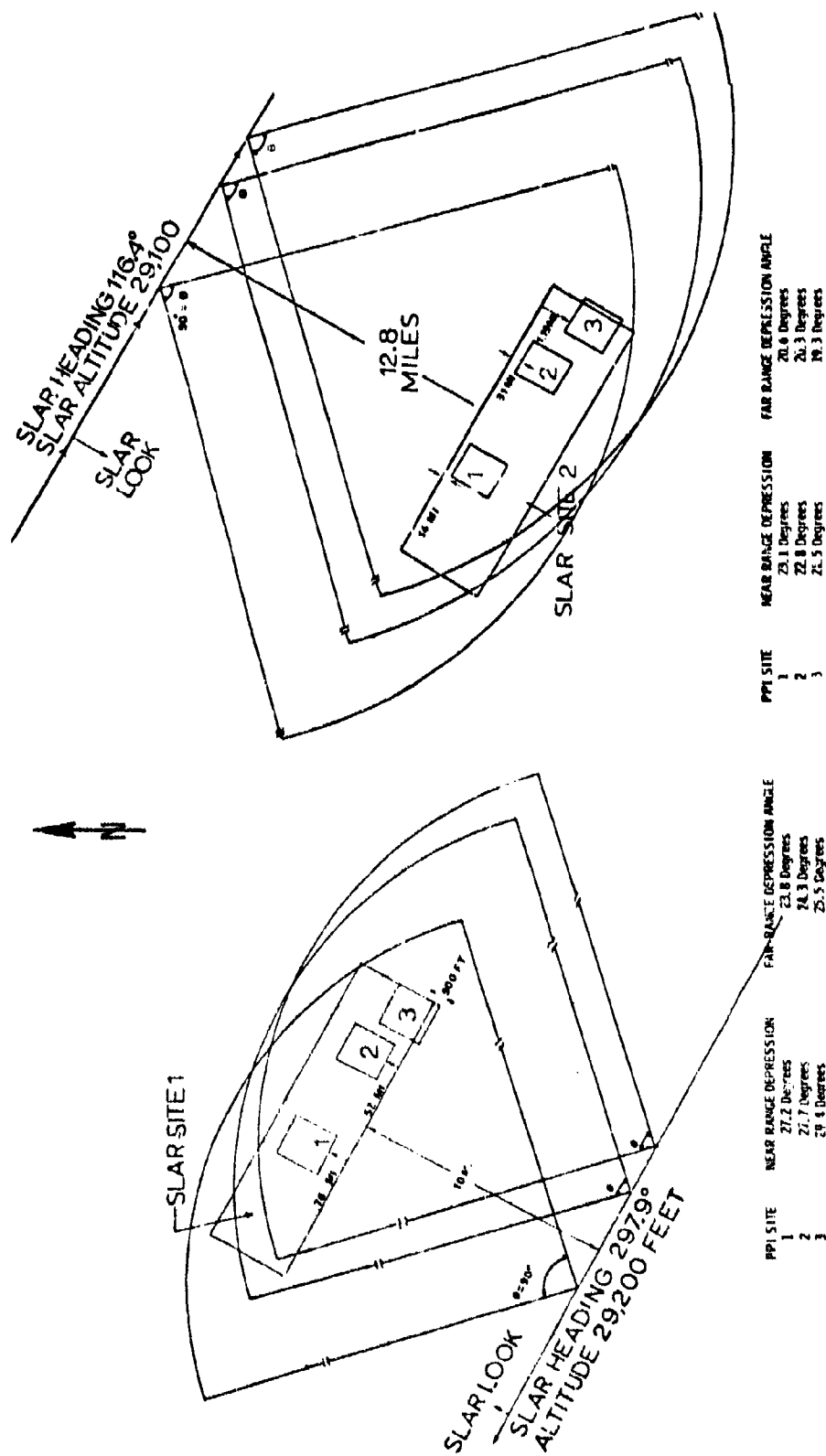


Figure 13.

areas similar to the form of the original ground truth data base. Therefore, the ground truth data may be processed in a serial manner. The PPI model, on the other hand transformed the ground truth data from rectangular coordinates into a radar data base in polar coordinates. This transformation allows one to model the varying look direction and changing resolution cell size and aspects peculiar to the forward scanning format of PPI imaging systems.

There are two broad categories for comparison of these two image outputs shown in these figures (14 and 15). The first is an analysis of relative greytone differences between different categories in the target scene. The second area to be studied is geometric fidelity to see if the transformation from rectangular coordinates to polar coordinates and back again for display purposed created any distortions in the output images of the PPI simulations.

It is not possible to compare absolute greytone values between the SLAR images and those of PPI because of the difference in antenna patterns for the two systems (PPI used $\sec^2\theta \csc\theta$ while the SLAR model incorporates a $\sec^2\theta$ function). Instead look at the relative change from one field to the next in one image and compare it to the change between the greytones in those fields in the reference image. Area I, around the river, in both Figure 14 and 15 is the best area for this comparison because of the large number of categories in close proximity. The changes in greytone are very similar in the two images. Also, notice that field boundaries do not suddenly appear or disappear between the two sets of images.

Another crucial factor in radar images is the occurrence of shadows. Areas II and III along the shore of the reservoir in both figures, are best for studying the effects of shadow. In both the baseline images and the PPI images, drainage patterns can be discerned in these areas by



I.



II.



III.



Figure 15. 297.9° Flight Heading PPI Validation Scenes.



I.



II.



III.



Figure 11. 116.40 Filtered Test Data PPI Validation Scenes.

the shadowing effects although it is somewhat obscured by tree cover. In Area I the shadow resulting from stands of trees in predominately agricultural areas is displayed in both the SLAR and PPI images.

Maintaining geometric fidelity in the PPI images in spite of the internal data transformations inherent in the PPI model is of great importance. There are two aspects to this question: 1) Insuring that portions of the image are not rotated or otherwise distorted; and 2) determining that image detail is not lost in the transformations. Area I is most appropriate for checking that rotations and distortions have not occurred. There are numerous boundaries in this area in the SLAR baseline images. Had any errors occurred they should be visible along some or all of the boundaries. However, the size and shape of each area in the reference images correspond favorably to the corresponding area in the PPI image. Areas II and III exhibit a large amount of detail along the shoreline of the reservoir. Again, each little inlet found in the simulated SLAR image can be found in the corresponding portion of the PPI simulated image.

In summary, very few differences, if any, can be detected between the simulated SLAR images and the simulated PPI images. The result of this validation, simply stated, is that the PPI model implementation is consistent with the implementation of the model for SLAR applications. The validation of the SLAR model against real radar imagery reported in Section 2 provides strong evidence for the accuracy of the general point scattering model for radar simulation. Since the PPI model is merely another implementation of the same model, if the implementation is accurate (i.e., no software errors or faulty assumptions) then that application should also be accurate. At a later date it would be very useful to have real PPI imagery available for a test site to continue the validation and confirm the results claimed here by inference.

4.0 *REFERENCE SCENE SIMULATION: QUANTITATIVE TEST

The purpose of the work reported in this section was to apply quantitative measurement techniques to images produced by the point scattering radar image simulation model by applying the model to formation of reference scenes for a terminal guidance test using the Correlatron. The scope of this work was limited to reference scenes (simulated radar images) formed from one set of flight parameters (e.g., altitude). All the work reported in the previous sections appealed to subjective comparisons between real and simulated radar images (i.e., qualitative comparative analyses were performed) for validation of the results. The results of these analyses were shown to be very good, indicating success in using the point scattering model to simulate both SLAR (Side-Looking Airborne Radar) and PPI (Plan-Position Indicator), and are presented in Sections (2.0) and (3.0), respectively. However, as with all subjective analyses, there are generally more questions raised than answered, and the data and analyses are always subject to different interpretations by different analysts. A major short-coming of qualitative image analysis is that it relies heavily upon the experience, interpretation ability, thoroughness, a priori knowledge of the image content, and intuition of the analyst. No matter how carefully (within the normal limitations imposed by manpower and computer resources) these analyses are structured and conducted, the results are always questionable. This first quantitative test of the point scattering radar image simulation model was conducted to partially allay criticism of the qualitative comparisons and inferred results reported in the earlier sections and partially to test the model against real-world problems. The quantitative test consisted of measuring the cross correlation between a simulated radar image (reference scene) formed by the point scattering method and a real radar image of the same scene. The goal was both to validate the point scattering radar image simulation model as well as to produce reference scenes.

Many ways exist, both optically and electronically, to measure the

*"Reference Scene" is the name applied to simulated radar images which are formed for use on the Correlatron.

cross correlation between two images. The method selected in this work was to use a correlation device specifically manufactured to measure the cross correlation between two scenes. The device used is called a Correlatron⁷ and was physically located at ETL (Engineer Topographic Laboratories, the United States Army, Fort Belvoir, Virginia). The Correlatron is an electronic device which externally resembles a television camera tube, but its internal construction and function are quite different. The function of the Correlatron is shown conceptually in Figure 16; the Correlatron accepts two image inputs and determines the cross correlation between them. In this figure the Correlatron is shown as an electronic "black box" having two inputs and one output. One of the inputs is shown to be a real radar image. The video output voltage ($T_R(x,y,t)$) of the radar receiver is applied to a LED (light-emitting diode) which generates a beam of light when a target-echo is received, or no light when there is no return. Quoting from the Aviation Week article, "This beam of light impinges on the photo-cathode to generate electrons, which in turn are caused to scan by the Correlatron deflection system so as to 'paint' the equivalent of the real-world radar display on the storage screen." The article further says that the electrons emitted by the photo-cathode ". . . are then attracted to a dielectrically coated fine wire mesh that is at a positive potential so that the image is stored on the mesh in the form of many different electrical charges. Typically the mesh consists of 500 to 1,000 wires per inch, but up to 2,000 per inch have been used to achieve extremely high resolution."

Once the real image is placed on the storage screen, then the simulated radar image (called a reference scene) is projected onto the photo-cathode and the resulting pattern of electron emission is deflected to correlate it with the real-world radar image on the storage mesh. In

⁷ Klass, Philip J., "Guidance Device Set for Pershing Tests," Aviation Week and Space Technology, May 12, 1975.

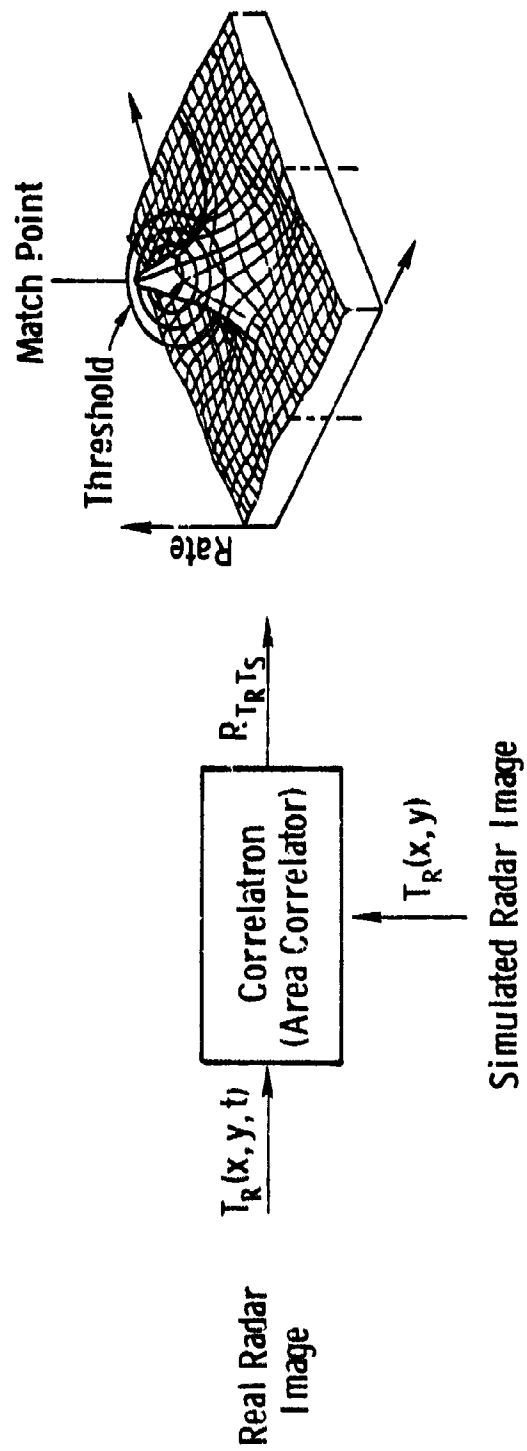


Figure 16. Conceptual View of Correlation

Figure 16 the simulated radar image input to the Correlatron is shown as a video voltage ($T_s(x,y)$). This is conceptually accurate but not strictly true. The simulated radar image is actually photographically provided to the Correlatron by optically projecting a transparency onto the photocathode. The electron current produced by the photocathode then produces the voltage ($T_s(x,y)$) of the simulated radar image.

In this way the cross correlation between the real radar image and a simulated radar image is measured by the Correlatron. The output of the Correlatron is the two-dimensional cross correlation ($R_{RTS}(x,y)$) as a function of position. The output is shown conceptually in Figure 16. The reference scene (simulated radar image) is said to be "good" if the cross correlation peak (output of the Correlatron) is greater than some threshold value (also illustrated in Figure 16). If the correlation peak doesn't exceed the threshold value, it is not obvious what this means. It is not so clear cut as "good" or "bad". Because of the complexity of the test system, if the criteria are not met the reason(s) for failing to meet the criteria may relate to any part, or all parts, of the test system. The failure may be traceable to the real image which served as input (radar system, image acquisition and storage techniques, anomalous features, etc.), to the simulated radar image (data base, radar simulation parameters, microwave reflectivity data, simulation model, implementation of the simulation model, etc.), to the reference scene input system (digital format, image brightness dynamic range, quantization level, etc.), or to the Correlatron itself (non-linearities in shading, photo-cathode operation, and storage, quantization level, image brightness dynamic range, deflection system, interaction between real and simulated image during measurement of cross correlation, etc.). In fact, so many variables interact in this test that it can be argued that the test is less a quantitative validation of the general point scattering radar image simulation model and more (much more) a test of a specific application of the model (in particular, a test of the software implementation of the specific application) together with the

supporting system hardware required for this model. What is really being tested are the concepts and techniques involved: The reference scene generation, the real-world image acquisition, and the correlation concepts and techniques. Thus, if the cross correlation test fails, not much can be inferred about the point scattering simulation method. If however, the test is successful, it can be inferred immediately that the point scattering radar image simulation model is a valid simulation model for this application. The better the degree of correlation of our reference scenes with "live" radar data, the greater the quantitative validation of our simulation model: It correlates well with "live" video data collected by a real PPI from the same scene.

It should be noted at this time that this task represents the first application of the point scattering radar image simulation method to model "real world" processes. In all previous work, including Sections 2. and 3. of this report, the radar image simulation model represented ideal, or perfect, systems. This is the first time that the model doesn't represent an ideal system. Not all characteristics of the model developed for this task represent real, instead of perfect, systems for they were not all known. But, for the major characteristics, this is true. For the total model, it's a mixture of real and ideal system characteristics. The system being modeled is the PPI radar, the ground test site, and the Correlatron. Real aspects of each of these have been included in the model developed. For instance, the resolution of the PPI system forced averaging independent cells (real world process) but the details of antenna and transmitter were unknown, and, thus, assumed ideal. The radar return categories in the test site were identified (real world) and assumed to be homogeneous (ideal). The Correlatron was assumed to be an ideal electronic "black box". The PPI image format together with reference scene requirements caused modifications to be made to the general model. These modifications were incorporated into the software implementation of the model and were essential to model the "real world" processes.

This points out a tremendous advantage of our radar image simulation method. It has been said before, but this is the first proof of the assertion that this model is mathematically rigorous! It is only necessary to define the characteristics of the real system being simulated and how they depart from the ideal case, then to alter the basic model accordingly. Thus, this model serves as the basic building block to describe any radar imaging system.

The candidate scenes (reference scenes) have been prepared and the digital magnetic tapes containing these scenes have been sent to EFL for testing on the Correlation. Preliminary results indicate excellent correlation. More detailed analysis of the results are pending.

4.1 Work Plan

Successful completion of this task required coordination and cooperation between the Kansas Simulation Group at the RSL (Remote Sensing Laboratory) and ETL (Engineer Topographic Laboratories). We were responsible for forming reference scenes and the ETL was responsible for testing them on the Correlatron. Figure 17 illustrates the conceptual flow of work performed. Both the activities performed at the RSL and at ETL are shown. As can be seen by reference to Figure 17, the work performed at RSL falls into four major categories: (1) Produce data base; (2) Develop simulation software; (3) Obtain terrain data; (4) Produce simulated radar images. Similarly, it can be seen that the activities performed at ETL fall into two categories: (1) Produce reference scene film; (2) Run Correlatron tests.

The first task accomplished was production of a ground truth data base. Before this task could be started, it was necessary to select a suitable test site. The selection criteria were established by the necessity for physical realization of the test. This necessity dictated that the primary site selection criteria were: (1) Real radar video data of the test site must exist; (2) The test site must be representative of the complexity and mixture of features normally found in radar images; (3) Source data from which a ground truth data base could be constructed (both elevation and planimetry) must be available; (4) Empirical differential scattering cross-section (σ^0) data (or suitable theoretical scattering models) for the scattering types contained in the selected area must be obtainable. All of the requisites, except criterion (4) were found to exist for a test site centered around the Pickwick Dam located in Tennessee. A ground truth data base was constructed of this site. The problems raised by the lack of σ^0 data for this site were resolved¹¹ by appeal to theory, the literature, and intuition.

¹¹ Abbott, J. L., R. L. Martin, M. McNeill, V. H. Kaupp, and J. C. Holtzman, "Backscatter Data for the Digital Radar Image Simulation of the Pickwick, Alabama Site," TR 319-7, Remote Sensing Laboratory, The University of Kansas, Lawrence, Kansas, February, 1977. Included in Appendix G, Vol. II, ETL TR-0118.

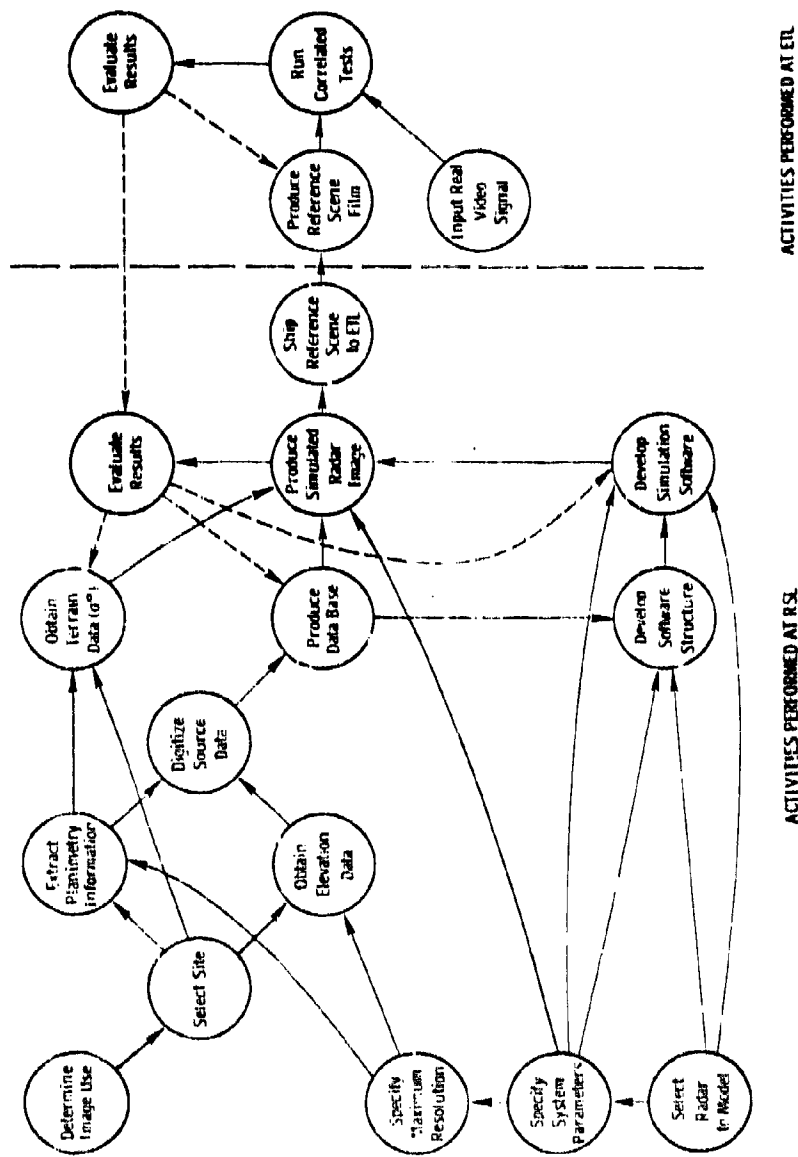


Figure 17. Work Plan - Terminal Guidance Task

Before construction of the data base could be started it was also necessary to select a radar system to model, to specify the system parameters, and to specify the maximum resolution requirements. Selection of a radar system (and, of course the system parameters including resolution) was dictated by satisfaction of criterion (1) above. Once real radar video data were obtained for a test site, the system parameters and resolution were automatically accounted for. Thus, these two separate paths, shown in Figure 17 culminating in producing a data base, were simultaneously satisfied.

After selection of a test site and specification of the radar system parameters, work was started on construction of the ground truth data base. Elevation data were obtained from ETL for the topographic area selected (these data were stored on computer-compatible digital magnetic tapes) and work was initiated at RSL to extract the radar planimetry data (ground return categories pertinent to an imaging radar system) from source data (maps and aerial photographs). The planimetry data were digitized and organized into a four-dimensional matrix compatible with the elevation data. The digital planimetry and digital matrix (the dimensions were: range, azimuth, elevation, category) were stored on computer-compatible magnetic tapes. These magnetic tapes are the ground truth data base of the Pickwick Dam test site. They contain in computer-compatible format the location, elevation, and radar return category of each point on the ground in the test site. As can be seen in Figure 17, several tasks were performed in parallel with construction of the data base. The first of these was development of the simulation software. Even though the point scattering radar image simulation model is completely general and rigorous, it is always advantageous to develop unique software for each specific application. These advantages primarily are owing to simplifications which can be incorporated in the software due to modeling a specific radar thereby making it a cost-effective, specialized package. The Correlatron also imposed some unique requirements on the simulation model. These requirements, by themselves, dictated development of specific software for forming reference scenes. Thus, special simulation software were developed to produce reference scenes. The second activity

performed in parallel with construction of the data base was obtaining terrain data. An investigation was conducted into the availability of empirical scattering cross-section (σ^0) data for the types of radar ground-return scattering categories found to exist in the data base area (Pickwick Dam test site). The literature was searched for empirical data and applicable theoretical models. The Study was conducted and applicable data were obtained.

Upon completion of these three basic activities (data base construction, simulation software development, terrain (σ^0) data acquisition) it became possible to perform the fourth (i.e., to produce test reference scenes). Test scenes were produced and evaluated, and problems and errors were corrected. A final set of reference scenes were formed, stored on digital magnetic tape in a computer-compatible format, and sent to ETL for testing on the Correlatron against "live" radar video data.

4.2 Reference Scene Data Base

A ground truth data base was constructed of the topographic area in the states of Tennessee, Mississippi, and Alabama centered on the northwest corner of the Power House Building at the Pickwick Landing Dam across the Tennessee river. After specification of the test site and radar system parameters, source data were acquired from which the ground truth data base could be built. Construction of the data base was separated into two halves. The first half was acquisition of elevation data which accurately modeled the relief present in the topography of the test site. The second half was construction of a feature map which accurately represented the geometry, location, and description of natural and man-made targets present in the test site. Details of the construction of this data base are reported in Section 5 and in Volume II.

4.3 Reference Scene Simulation Model

Referring back to Figure 17, it is seen that while the ground truth data base was being constructed the reference scene simulation model was being developed. Recall that the purpose of this task was to make quantitative measurements of the quality of simulated radar images (reference scenes) and real radar video data of the same site. To accomplish this the reference scene simulation model had to represent accurately the operating parameters and formatting requirements of both the Correlatron and the real radar system. A special reference scene simulation computer program was written to incorporate these features¹⁸. The details of this effort will not be repeated here, they are reported in Volume II.

The test site selected for the test of the simulation model was the Pickwick Landing Dam area. Radar video data of this site had been collected by a PPI (Plan Position Indicator) radar and stored on magnetic tape. It was proposed to form simulated radar images of the Pickwick site and use the Correlatron to measure the degree of cross correlation between them and the real PPI video data.

Normally when modeling a system, calibrated system data and transfer functions are used to develop a model (computer program in this case) which approximates "real-world" events. In this case, only minimal information was available about the transfer functions of both the real PPI radar and the Correlatron. Yet, features of both had to be incorporated into the simulation model. To overcome this lack of system data, the reference scene simulation software have been developed assuming a "perfect" system. That is, the PPI radar was assumed to have an antenna pattern with constant gain across the azimuthal beamwidth and with zero gain elsewhere, and the gain was assumed to be a nominal $\csc^2 \theta \cos \theta$ (θ = depression angle) pattern in the range direction. The return power

¹⁸ Komp, E., V. H. Kaupp, J. C. Holtzman, "Digital PPI Model for Radar Image Simulation and Results", TR 319-19, RSL, The University of Kansas, August, 1977, Included in Appendix J, Vol. II, ETL TR-0118.

(P_R) Incident at the antenna terminals was assumed to be linearly related to the intensity (I) incident on the recording film (i.e., the receiver transfer function was assumed to be linear in the portion of the dynamic range used: $I = MP_R$; where M is a constant of proportionality). The transfer function of the Correlatron was assumed also to be "perfect."

It was assumed that the mechanics of sampling the reference scene did not degrade the scene; that the input paths were identical for both the "live" video and "reference video;" that the process of converting a reference scene stored on photographic film to a "video" signal was linear; and that the process of measuring the cross-correlation did not significantly degrade either, or both, the "live" or the "reference" scene.

These assumptions though necessary, do not at first appear to be realistic. They are too simplistic. However, the true test of a model is how faithfully it predicts "real-world" phenomena, not how faithfully each and every component and sub-component is reproduced. Just as all mathematical models are abstractions of reality, so is the reference scene model developed and implemented for the Correlatron test. The extent to which this model faithfully predicts "real-world" events is directly related to the validity of many assumptions and simplifications. Among these are: (1) Parameters and transfer function of the real PPI radar; (2) Parameters and transfer function of the area correlator; (3) Validity of the empirical differential scattering cross-section data; (4) Accuracy of the reference scene ground truth map; (5) Software implementation of this specific application of the general point scattering simulation model; (6) Finally, validity of the point scattering simulation model.

This test of the point scattering radar image simulation model was designed to be a blind trial: No a priori knowledge about the flight parameters of the PPI data from the target were made available to Kansas. Only two pieces of information were provided: (1) The altitude from which the PPI data were taken was 4,000 feet, and (2) The entire PPI image would lie within a 2.75 mile radius circle centered on the

northwest corner of the power house of the Pickwick Landing Dam test site. This means that the reference scene simulations had to be constructed as nearly omni-directional as possible, since the direction of approach was not known. Obviously radar imagery is exceptionally directional. This property is caused by the fact that the radar provides its own source of illumination. Thus, the direction of layover and shadow are determined by the look-direction of the radar. Nevertheless, the reference scenes were formed assuming that the real imagery were centered on the power house looking radially outward.

The PPI radar used to collect the "live" video data of the Pickwick site had an unusual image scan format. It recorded data for a full circular sweep of the scene (360°) instead of the normal sector (90°) associated with PPI radars. This special scan is illustrated in Figure 18 and is compared to a normal PPI scan. Additional details of the image format are shown in Figure 18. As can be seen by reference to this figure, this PPI radar imaged the terrain within an annular ring bounded on the near range by 35° incidence angle and on the far range by 65° . The terrain lying within the circle bounded by 35° was not imaged; this created a hole in the real image. At 4,000 foot altitude (the altitude at which the "live" video data were collected) the radius to the far range extent of the PPI image is approximately 1.6 miles. Recall that the only additional specifications were that the entire real PPI scene would lie within a circle of $2\frac{3}{4}$ mile radius centered on the power house. The geometry of the situation is shown in Figure 19.

As shown in Figure 19, the direction of approach of the real PPI radar and the center of the real imagery, being unknown before forming reference scenes, might occur any place within the reference scene. This presented a formidable problem for the reference scene software because the reference scene had to be capable of a degree of cross correlation with the real image in excess of the threshold. These conditions (uncertainty of approach and center of the real PPI video signal) imposed necessary conditions on the simulation effort: (1) No "holes" were allowed in the reference scene even though one existed in the real

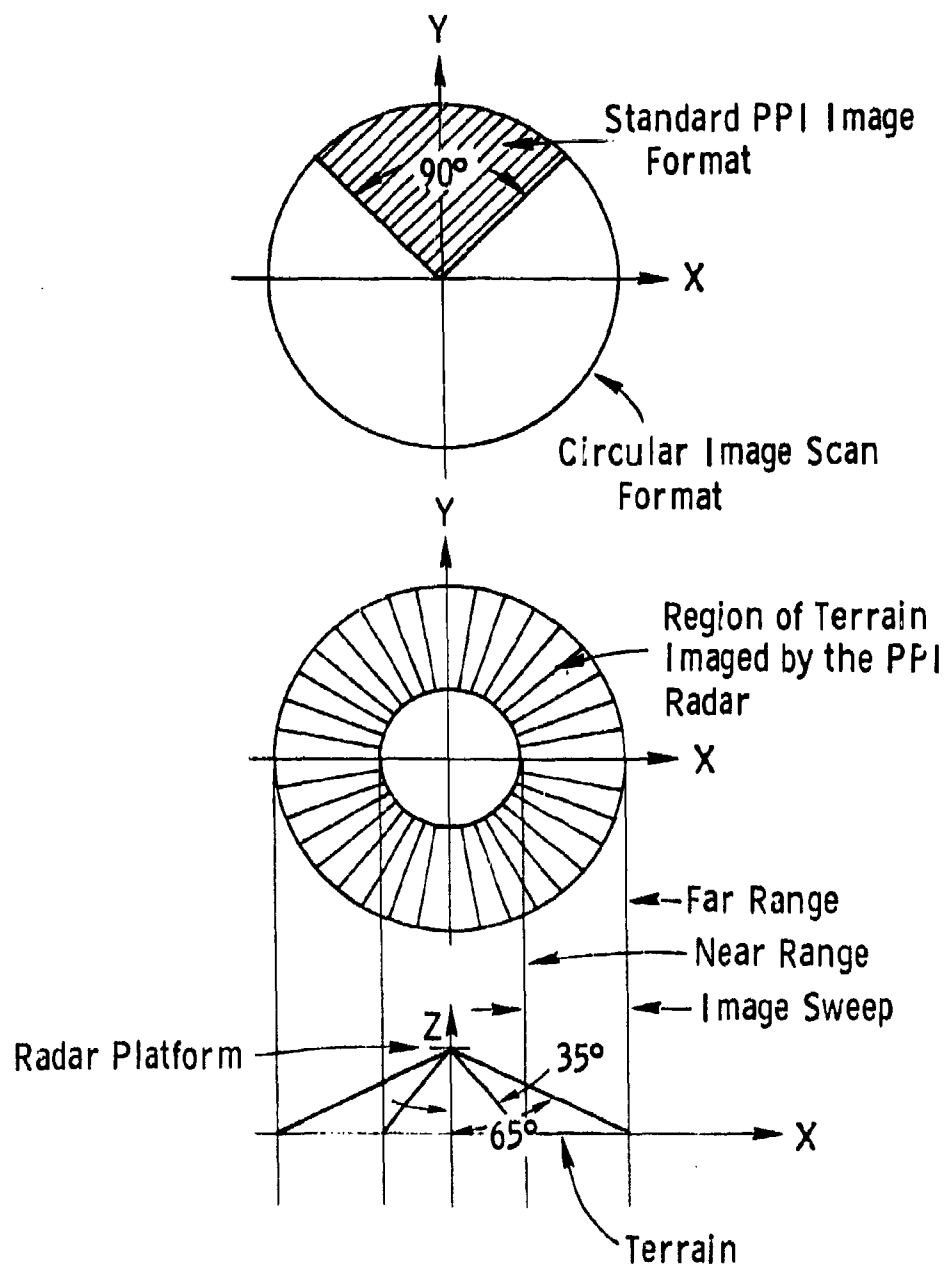


Figure 18. Special PPI Image Format

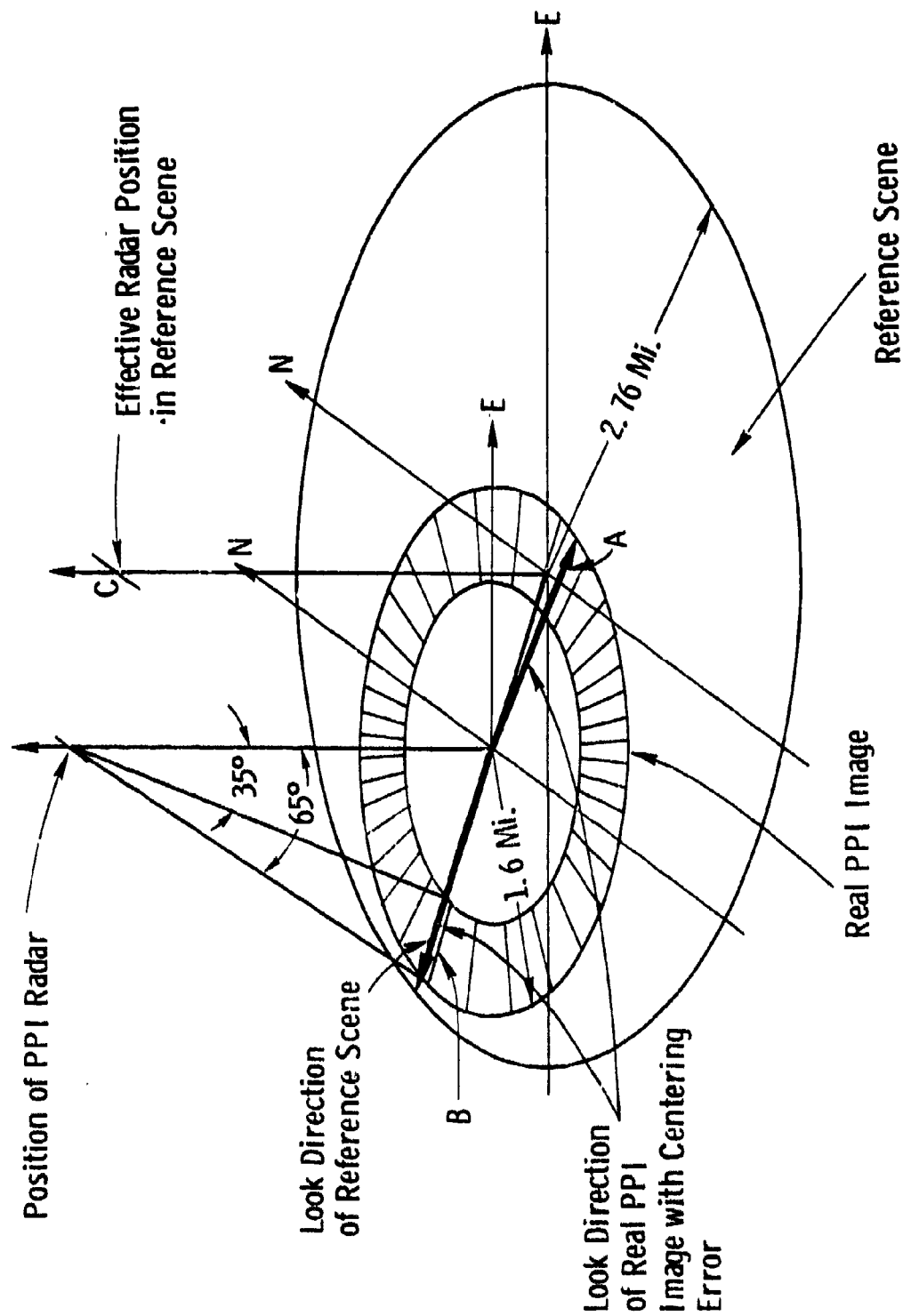


Figure 19. Comparison of Reference Scene to PPI Radar Image Format

data; (2) the reference scene must be larger than the real PPI scene to accomodate "centering" errors; (3) Angles of incidence of the real data were in the range 35° to 65° meaning all of the reference scene should also be in that range even though the actual geometry of the reference scene would decree a range from 0° to 75° .

These conditions were all incorporated into the software implementation of the point scattering radar image simulation model developed to form reference scenes. The basic approach undertaken was to minimize differences between the simulated images and real images.

Consider the magnitude of the problem. If the PPI radar approaches the target (northwest corner of the power house) off course as shown in Figure 19, then look direction errors between real and reference scenes between 0° and 180° occur. Look direction affects are most significant in ground scenes having considerable local relief because the direction and length of shadows (and layover) in radar images are determined by the look direction. Figure 20 illustrates the problem for a look direction error of 180° between the real and simulated radar image. The condition shown in Figure 20 might occur anyplace on the line segment labeled A in Figure 19. As the line segment A is rotated around the center of the real image in Figure 19, it can be seen that the look direction error will decrease from 180° to 0° when it is aligned with the segment labeled B. Test sites having significant local relief variation would appear very different depending upon the direction of approach of the real PPI radar. Fortunately, the Pickwick test site had only a modest amount of local relief, so this is one problem which was not tackled during this quantitative validation test of the point scattering radar image simulation model. But it certainly warrants attention if a test site having a considerable amount of local relief is selected at some point in the future.

Other aspects of the look direction problem were treated and their impacts minimized in the software implementation of the simulation model. As should be obvious from either Figure 19 or 20, as the look direction

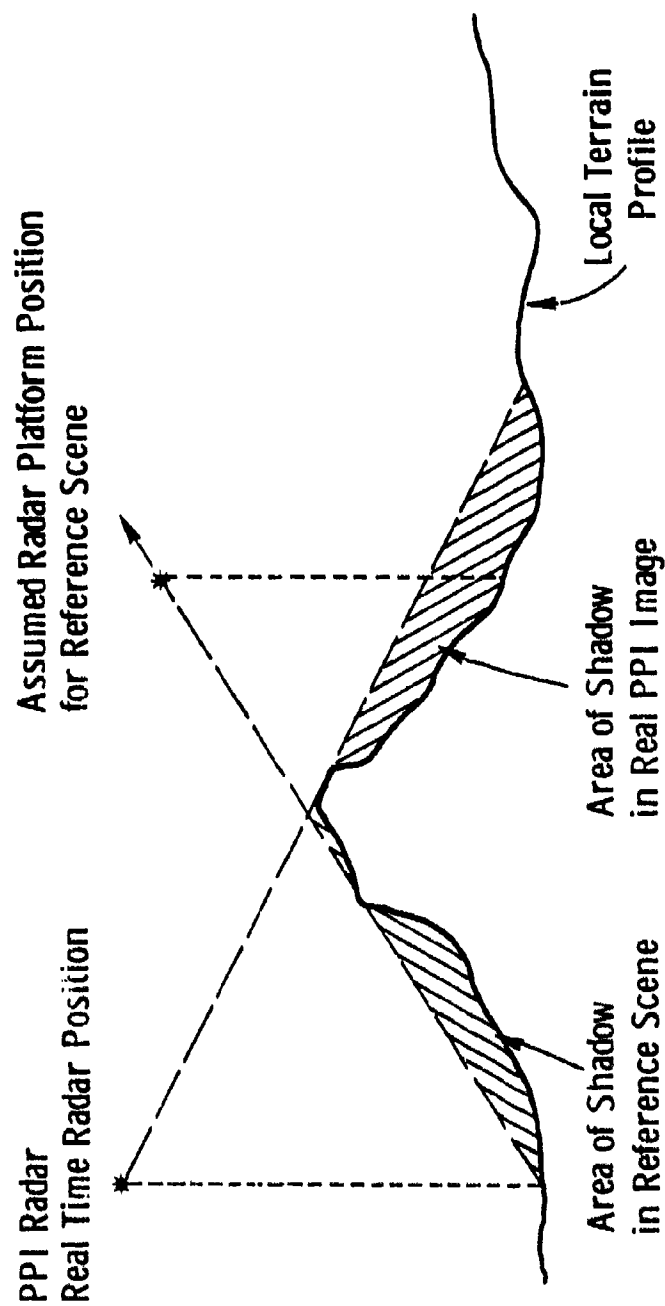


Figure 20. Effect of Look Direction Error

changes so also does the incidence angle change. Consider the circle of constant 65° incidence angles of the real PPI image shown in Figure 19. Imagine a line drawn from the point describing the effective position of the radar in the reference scene (point C) to the 65° circle. As the imaginary line, pinned at C, traces out the 65° circle it is easily seen that the angle of incidence in the reference scene changes from approximately 0° to approximately 65 to 70° while in the real scene it is constant. As is well known, ground radar return data (σ°) for the same target varies by many decibels over the range 0° to 70° incidence angle. For this reason, the reference scene simulation software could not be set up to produce a simulated image according to the actual geometry of the problem. If this were done, even if the 65° circle happened to fall always on the same category and thus would be a constant shade of grey in the real image, the 65° circle would trace out a path on the reference image which conceivably could vary from black to white.

In the range of incidence angles in the real image, 35° to 65° , most radar ground return curves are relatively linear and have relatively shallow slopes (nothing factual or quantitative implied here, this is a qualitative argument). The antenna function in the range direction (look direction) over this same range of incidence angles tends to compensate for the slope of the σ° data producing, for a number of ground return categories, a relatively uniform return thereby minimizing the problem caused by different look directions. For these reasons, it was decided that the minimum angle of incidence in the simulated reference scene would be 35° and the maximum would be 65° . The area in the reference scene lying between 35° and 65° angle of incidence was simulated normally. And, the area lying outside the 65° circle was all simulated as if it were 65° . This solution did not attempt to model the real video exactly but, rather, did attempt to minimize discrepancies between the reference scene and the "live" video produced in flight.

This is not to say that local slope variations were not accounted for; they were, indeed, accounted for. What is meant is that the incidence

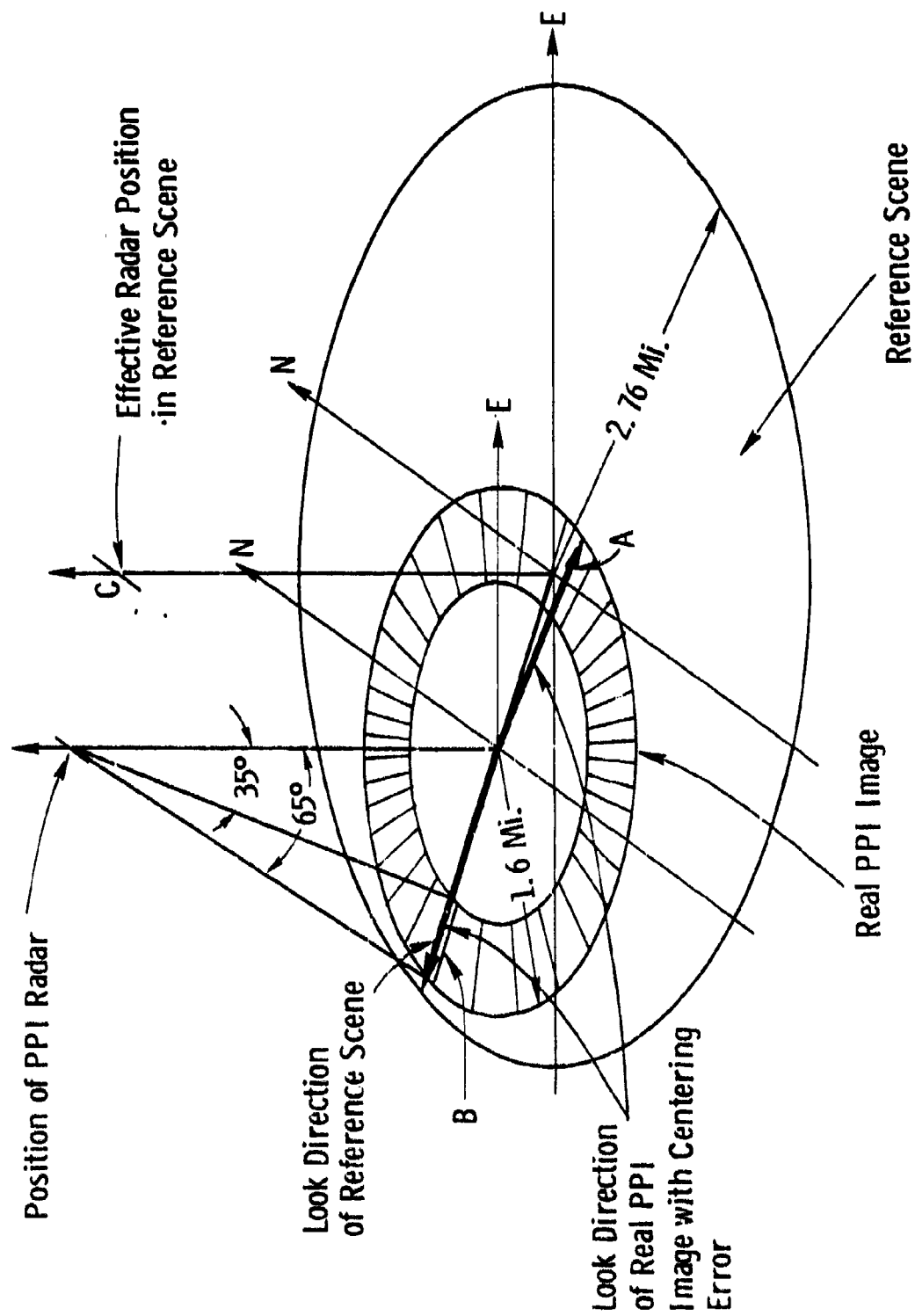


Figure 19. Comparison of Reference Scene to PPI Radar Image Format

angle (θ) between the antenna "boresight" and the local vertical was always in the range 35° to 65° . Local slope variations then altered the incidence angle to the local incidence angle (θ_λ), just like in the simulation models described in Sections 2 and 3. In fact the limitations imposed on minimum and maximum values of θ_λ come strictly from the local relief in the scene.

This solution to the angle of incidence problem created data handling problems for the computer program, and data base problems. For instance, 35° angle of incidence specifies a resolution cell size for short pulse and narrow beamwidth radars. Yet, the geometry of the data base dictates that as data base cells get closer to the center (in polar coordinates) they get larger in the range direction and smaller in the azimuth direction. This problem was minimized by accurately modeling another feature of the real PPI; it recorded data in ground range mode. Ground range mode means that (for a flat earth) equal size objects located in the near and far range will have equal sizes in the image format. This is normally accomplished by applying a nonlinear sweep to the electron beam of the viewing CRT. But, for simulation purposes, it simply meant building the simulation data base with equal size cells in the range direction. It should be noted at this time that in the presence of terrain having significant relief, ground range mode introduces large distortions, a fact to keep in mind for such future sites.

In summary, the general point scattering radar image simulation model was specifically tailored to the special requirements imposed to simulate reference scenes for use on the Correlatron. The software implementation of the reference scene simulation model included the following special features:

- (1) 360° PPI image scan format;
- (2) Simulated area was larger than the real image to allow "centering" errors;
- (3) No holes allowed, the reference scene was completely filled;
- (4) Minimum angle of incidence = 35° ;

- (5) Maximum angle of Incidence = 65° ;
- (6) Local angle of incidence was properly treated;
- (7) In the reference scene, the area between 0° and 35° was simulated at a constant 35° angle of incidence;
- (8) The area between 35° and 65° was simulated normally;
- (9) The area outside 65° was simulated at a constant 65° ;
- (10) Variations due to angle of incidence differences between real and simulated image were minimized;
- (11) Reference scenes were formed in the ground range mode;
- (12) Layover and shadow were properly included;
- (13) Local slope variations in the terrain were properly included.

4.4 Terrain Return Data

After specification of the operating parameters (frequency and polarization) of the real PPI radar and after identification of the different categories of scatterers located in the proposed scene to be simulated, it was necessary to obtain appropriate terrain return data. The different categories of radar scatterers identified in the Pickwick reference scene test site were separated into two major classes: (1) Distributed targets, and (2) Cultural targets.

Distributed targets are homogeneous regions, each with a single microwave scattering category throughout its total extent. Each homogeneous region must be at least as large as the resolution element of the radar being modeled, the individual scattering centers located in a resolution cell must be randomly located, and there must be a large number of scattering centers in each resolution cell within a homogeneous region. When these conditions are satisfied, an average value of the scattering cross-section (σ°) can be used to model the radar return from these homogeneous areas of terrain (distributed targets). Most of the terrain located in the reference scene data base of the Pickwick site satisfied these criteria. Thus, differential scattering cross-section data (σ°) were used to model

the radar return properties of the terrain in the reference scenes formed from the Pickwick data base. Actually, empirical σ^0 data were used (as opposed to theoretical). These data were obtained from the literature and from the RSL data bank¹¹. The best match that could be found between available empirical σ^0 data and the identified distributed targets in the Pickwick site was sought. The empirical σ^0 data was not extracted from radar imagery of the Pickwick site or any other site. The details of what σ^0 data were used to form reference scenes are presented in Volume II¹¹.

Cultural targets are here defined to be manmade objects and features. Their radar returns are characterized by specular reflection. They cannot be modeled as distributed targets. To model cultural targets by digital computer is an exceptionally complex task requiring tremendous detail about each such target to be included in the data base. An evaluation was made of the kinds of cultural targets present in the Pickwick site, their orientations, and the number of them. It was concluded that symbolic modeling of these targets would provide the best probability of correlation. By symbolic modeling we mean that the location of each cultural target was pin pointed in the data base but the orientation, size, geometry, etc., was not. Cultural targets were assumed, for the purposes of reference scene formation, to be isotropic radiators having an effective differential scattering cross-section of +20 dB. This most certainly is not accurate. But, consider the task: Cross correlation with "live" video data with an unknown heading and arbitrarily located center with respect to the center of the reference scene. The orientation (not the location) of cultural targets was random. Given no a priori knowledge of the heading of the "live" data, it would not be possible to properly simulate all the corner reflectors,

¹¹Abbott, J. L., R. L. Martin, M. McNeill, V. H. Kaupp, and J. C. Holtzman, "Backscatter Data for the Digital Radar Image Simulation of the Pickwick, Alabama Site," TR 319-7, Remote Sensing Laboratory, The University of Kansas, February, 1977. Included in Appendix G, Vol. II, ETL TR-0118.

etc., of cultural targets to match the look direction of the "live" data. The best that could be done would be to accurately mark the location of them and assume them to be isotropic radiators. Then, given a direction of approach for the real data, those cultural features properly aligned would be white in the real data which, of course, would match very nicely with the simulation. Those not properly aligned would be some lower shade of grey which should still improve correlation. Thus, it was concluded that symbolic simulation of cultural features would enhance cross correlation between the real and simulated images, and this is the way they were treated when forming reference scenes.

4.5 Reference Scene Formation

After the radar system operating parameters have been specified, after the ground truth data base has been constructed, after the radar system and operating environment have been modeled and a software implementation has been developed, and after the ground return data (σ^0) have been obtained; the separate pieces can be put together and reference scenes can be formed. Figure 21 shows, in block diagram form, a conceptual model of reference scene formation. Figure 21 is an amplification of part of Figure 17, the block which states, "Produce Simulated Radar Images." As can be seen in Figure 21 there is a large degree of interaction between the three basic program inputs. As a brief review, the first data required are the radar system parameters and site of which the reference scene is to be built. Upon specification of these parameters, data base construction and radar system modeling are started. Once the ground return categories to be included in the data base have been identified, then the search for appropriate radar return data (σ^0) is started. After completion of the task of modeling the radar system, a software implementation of the model is developed. Upon completion of these four activities, the simulation system is ready to start producing reference scenes.

As previously noted, the Pickwick data base was constructed in a rectangular grid matrix. Recall that the real radar system used to

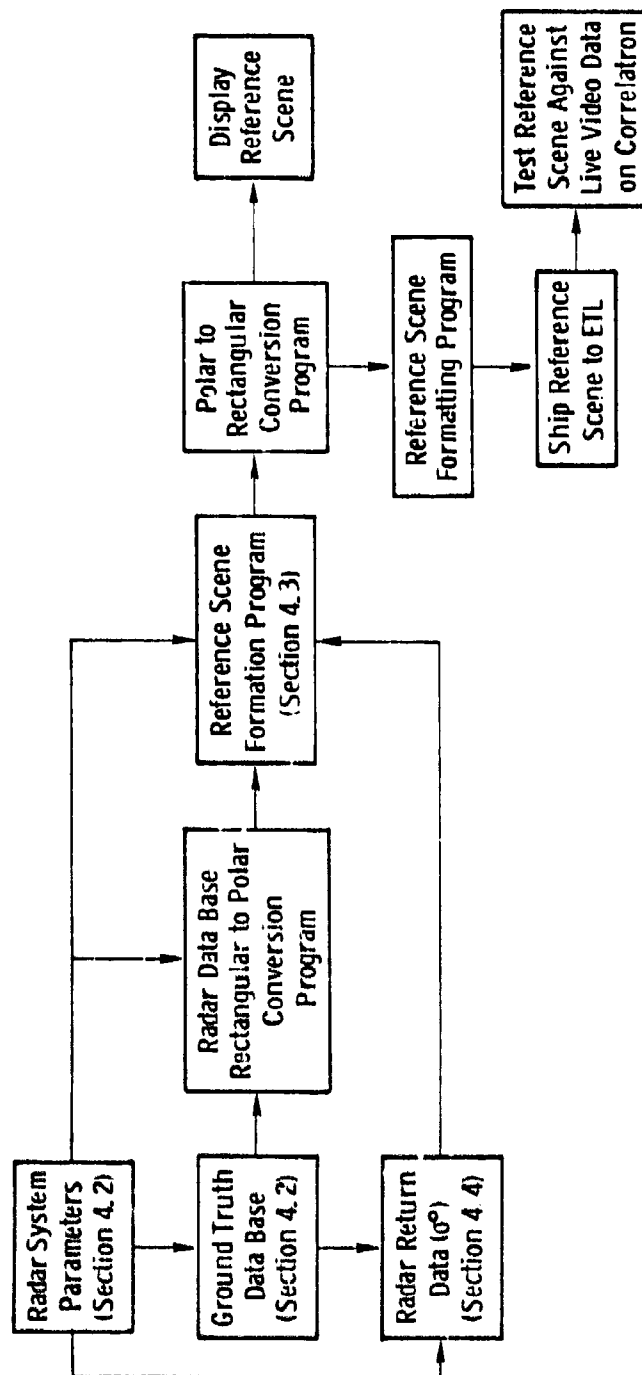


Figure 21. Conceptual Model of Reference Scene Format

collect the "live" video data of Pickwick was a PPI. These two facts mean that the data base must be converted from rectangular coordinates to polar coordinates for the reference scene formation software. A special rectangular-to-polar coordinates conversion program was written. Standard ("canned") programs were not used because of the very large size (number of data points) of the Pickwick data base (approximately 10 million data points). They would have cost too much to run and, thus, were not used. Instead, a special program was written¹⁸ which was much faster (and, thus, cheaper) to run.

To make reference scenes, the following sequence occurs; see Figure 21. A radar data base is made. Radar data base only means that it is in correct geometric format (polar coordinates) and has the correct resolution cell size for the radar being modeled. The radar data base is made by the rectangular-to-polar coordinates conversion program and is made from the ground truth data base and from specification of the resolution element of the radar being modeled. The output of this program (the radar data base) serves as one input to the reference scene formation program.

The reference scene program forms simulated radar images. It forms these images from the three sets of input data. First, the radar system parameters specify operating frequency, polarization, resolution size, flight altitude, flight location, flight orientation, flight heading, etc. are used together with the radar data base by the program to calculate all the intermediate data prior to calculating the final result. Such data as local slope, resolution cell area, local angle of incidence, radar angle of incidence, range to cell, etc., are calculated. The final step is to use these intermediate results with the backscatter data (σ^0) to compute the fraction of power reradiated back to the radar and process these data into the final result, the graytone values for each point in the scene. At this point, the reference scene has been formed. It is stored on digital magnetic tape in a polar coordinate system.

¹⁸ Komp, E., V. H. Kaupp, J. C. Holtzman, "Digital PPI Model for Radar Image Simulation and Results," TR 319-19, Remote Sensing Laboratory, The University of Kansas, August, 1977, Included in Appendix J, Vol. II, ETL TR-0118.

Next, the reference scene is converted into a rectangular coordinate system and stored on digital magnetic tape. The same program used earlier to convert the ground truth data base to a radar data base is used. This program converts the polar coordinate reference scene into a rectangular grid matrix of specified size and stores it on digital magnetic tape. The size of this matrix is determined by its use. As can be seen in Figure 21, several alternatives exist at this point: The reference scene can be displayed on conventional equipment such as RSL's IDECS^{*} or it can be tested on the Correlatron. If it is desired to display the reference scene for evaluation at RSL, then the size of the rectangular matrix is determined by display limitations and evaluation considerations. If the scene is to be tested on the Correlatron, then the size of this matrix is pre-determined. Regardless of which (or both) alternative(s) is (are) desired, a reference scene of the Pickwick test site has been produced at this time. The work remaining, now, is to evaluate the reference scene tests on the Correlatron.

4.6 Results: Reference Scenes

Reference scenes have been produced for the Pickwick Landing Dam test site. These reference scenes have been properly formatted, stored on digital magnetic tape, and these tapes have been sent to ETL for testing on the Correlatron. The complete test results are not yet available, however, preliminary results are very satisfactory.

For the purposes of this report, a qualitative evaluation is given in lieu of the Correlatron results. (It is unfortunate that the quantitative results can't be given for they are very good, but circumstances beyond our control prevent it.) Five photographs of Pickwick reference scenes are presented in Figures 22-26. Before discussing the results, one problem that surfaced is discussed. Up until this work, we have modeled medium resolution radar systems. With medium resolution radars all of our important model assumptions and requirements are typically satisfied (Section 1.4). With this work we were modeling a coarse

^{*} Image Discrimination, Enhancement, Combination, and Sampling

resolution radar and some of the model assumptions broke down. We can only discuss this qualitatively (how it "looked") at this point, since quantitative data can't be invoked. But, the principle problem was resolution. Up until this time the resolution cell size specified by the system being modeled represented adequate sampling of the scene. Not so here. The system being modeled had a deliberately enlarged resolution cell; and for the purposes of radar image simulation, this cell size undersampled the scene by quite a large factor. This was apparent in early interim results because the scene looked like a "patchwork quilt." An investigation was conducted and it was decided that the correct way to simulate this radar would be to oversample the scene by a number of independent samples and average an appropriate number. This had been unnecessary in previous work for the results to "look" good. The antenna aperture length was unknown (azimuth resolution length) as was detailed information on the transmitter (i.e., was frequency averaging appropriate in the range direction?). Thus, a size of 100 feet in range and $1/2^\circ$ in azimuth was assumed for independent elements. The radar data base (not the ground truth data base; see Figure 21) was rebuilt to these specifications. The reference scene simulation software were modified to average a specified number of its nearest neighbors with each point: N in range, M in azimuth. Each point in the new reference scene, then, will be the result of averaging each point with N x M of its nearest neighbors. Since the antenna pattern wasn't known any better than the antenna length and transmitter details, the averaging was not weighted by the antenna pattern. For present purposes, the gain of the antenna had to be assumed constant over a size of N x M independent resolution cells. This clearly is a naive assumption, but it was essential for work to progress.

New reference scenes were produced using the increased resolution radar data base and the averaging capabilities. The results were startling to the eye: The blurring caused by averaging and increased information caused by finer resolution produced, to the eye, just

exactly the desired effect. The simulated radar imagery "looked" good.

Figures 22-26 have been produced using these techniques. These figures are high resolution photographs of the actual digital magnetic data tape sent to ETL for testing on the Correlatron. They are the qualitative results presented here to substantiate the claim of the work done. Pending word from ETL, these are the results. Figure 22 is a high resolution photograph of a reference scene of the Pickwick site made at full radar data base resolution (100 feet range by $1/2^\circ$ azimuth) and have no averaging performed ($M = 1$, $N = 1$). Figure 23 is a photograph of a reference scene made from an average of nine independent cells ($M = 3$, $N = 3$). Figure 24 represents an average of 81 independent cells. Figure 25, 121 cells. Figure 26, 99 cells.

5.0 CONSTRUCTION OF DATA BASES/FEATURES EXTRACTION TECHNIQUES

5.1 Background and Description

5.1.1 Data Base Definition

The ground truth data base is a major input requirement of the point scattering radar image simulation computer programs. Since the radar simulation model has been implemented on the digital computer, the data base must be in digital format. The data base can be considered to be a digital model of the physical (geometric) and radar return (dielectric) properties of the ground. It is a digital representation of the different features and elevation variations of the terrain present in the target scene.

This input data base contains information which represents the area to be simulated. Because the area to be simulated normally is a real scene somewhere on the surface of the earth, the data base should model a three-dimensional surface. However, an assumption was made that, for this application, the earth could be modeled as a two-dimensional surface with an orthogonal coordinate system. This assumption has been successful to date,

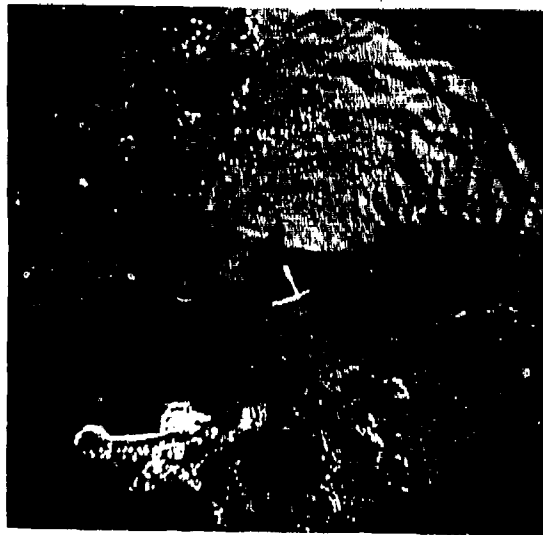


Figure 22 Reference Scene: Pickwick Site, Test 1
 Altitude: 4000 Feet, Frequency: X-Band
 Polarization: HH
 Resolution: Range=100 Feet, Azimuth= $1/2^\circ$
 Resolution Cells Averaged: 1

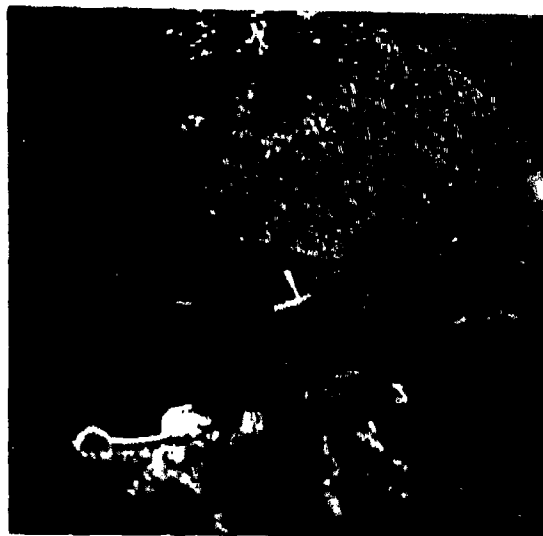


Figure 23 Reference Scene: Pickwick Site, Test 2
 Altitude: 4000 Feet, Frequency: X-Band
 Polarization: HH
 Resolution: Range=300 Feet, Azimuth= $1/2^\circ$
 Resolution Cells Averaged: 9



Figure 24 Reference Scene: Pickwick Site, Test 3
 Altitude: 4000 Feet, Frequency: X-Band
 Polarization: HH
 Resolution: Range=1100 Feet, Azimuth= $5\frac{1}{2}^\circ$
 Resolution Cells Averaged: 81



Figure 25 Reference Scene: Pickwick Site, Test 4
 Altitude: 4000 Feet, Frequency: X-Band
 Polarization: HH
 Resolution: Range= 900 Feet, Azimuth= $4\frac{1}{2}^\circ$
 Resolution Cells Averaged: 121



Figure 26 Reference Scene: Pickwick Site, Test 5
Altitude: 4000 Feet, Frequency: X-Band
Polarization: HH
Resolution: Range=1100 Feet, Azimuth=4 1/2°
Resolution Cells Averaged: 99

as the largest data base used to date for reference scene simulation has been 36 square miles. However, if areas to be simulated become large (750 miles), then this assumption might bear closer scrutiny.

The two-dimensional surface was chosen because it closely models the real world and has the most natural computer representation. This representation is the two-dimensional array, or matrix. Each entry in such a matrix has associated with it an X and a Y coordinate. These coordinates represent offsets in the two orthogonal directions (range and azimuth) from some predetermined origin. Thus, by defining the X-offset and Y-offset appropriately, this matrix will model any rectangular grid. In order to obtain an evenly distributed square grid, simply define the X and Y offsets to be the same. Another advantage to this scheme is that it is easily modified. For instance, if the data base needs to be transformed into a different resolution data base, then appropriate averaging or interpolation will suffice to perform the transformation and the new data base is in the same format as the old one. This two-dimensional representation also accurately represents the third dimension of height by including in the data value an elevation component. Another advantage of this data base format is that although the information is stored rectangularly, it does not have to be interpreted as a rectangular data base. For example, a polar data base can easily be stored in this format by using a $360 \times N$ matrix, interpreting the first component as degrees of offset (θ) and the second coordinate as distance from the origin (r).

The three simulation programs, SLAR, PPI, and terminal guidance, were designed so that they could all use the exact same data base as initial input. Thus, even though the terminal guidance and PPI radar simulation programs use polar coordinate systems rather than rectangular coordinate systems, the first step in those two packages is a rectangular-to-polar conversion step. In this way, one data base can be used to produce simulated radar images in any of the three radar image simulation formats.

Within any data base, each data item must contain an elevation value (as mentioned above) and a microwave return category. This second half of

the data item (microwave return category) refers to the geometric and electromagnetic properties of the ground cover, and equates to a categorization of relative microwave backscatter and return characteristics of different ground covers. The final data base, as input to the simulation programs, is stored on magnetic tape in physical block mode, the size and number of blocks known to the program beforehand. This, then, is what the final data base looks like.

Typically, this data base consists of a digital matrix containing four dimensions. These four dimensions are the range and azimuth coordinates, elevation, and radar backscatter category of each point on the ground. It is this matrix upon which the simulation program operates to calculate such parameters as look-direction, range, angle-of-incidence, shadow, layover, range-compression, local-slope of the terrain, local-angle-of-incidence, etc. After calculating these parameters, the simulation program obtains from the ground truth data matrix the radar backscatter category of each point in the scene. Only the backscatter category, not the σ^0 data, are included in the data base.

Upon calculation of all these parameters and specification of the backscatter category for a point on the ground, the simulation program requests σ^0 data (input from a σ^0 data file) and then calculates the graytone of that pixel in the image. This is repeated, converting information about each point on the ground into the appropriate graytone for each pixel in the image. Thus, the importance of the ground truth data base can be seen to span the radar simulation activities from geometric fidelity to graytone fidelity of the simulated radar images which are produced.

5.1.2 Background

Construction of the ground truth data base is a very large problem facing radar simulation. Since we implement our radar simulation program on the digital computer, the ground truth data base must be in digital form, compatible with the computer. The data base can be considered to be a digital model of the ground. This digital model as we develop it, is typi-

cally a four-dimensional matrix; two dimensions specify the range and azimuth of each point on the ground, another specifies the elevation of each point and the fourth describes the microwave category of each point. Construction of this digital ground model is a difficult, time-consuming problem.

This is especially so because of the way that data bases are constructed. They are, typically, built using manual techniques. Once the source imagery (photos, maps, etc.) have been obtained for a particular site, a photo-interpreter uses these imagery and his knowledge and intuition to construct a data base map of the area. This data base map is usually drawn by hand. Major features may be traced or transferred from the source imagery. Locations of minor features and subdivisions are usually subjective determinations by the photo-interpreter. The name most often applied to this task is feature extraction. Construction of this hand-drawn data base map is a major effort requiring judgment, accuracy, and knowledge of the area.

When this hand-drawn data base map has been finished, what we have is a symbolic radar map (category map) of the site. It is a line drawing of the boundaries outlining features present in the area (such as boundaries separating forests and vegetation). For use on the digital computer, this line drawing must be digitized and constructed into a digital matrix.

A large table digitizer is typically used to digitize the boundaries on the category map. A human operator traces each boundary with the cursor of the digitizer and the computer attached to the digitizer table periodically samples and records the position of the cursor. After digitization, we have a digital magnetic tape containing the sampled position points, all stored consecutively (serially), for each boundary in the category map. These serial digital boundaries must next be made into a digital matrix.

The magnetic tape containing serial boundary data are input to the computer. The computer is used to sort these data and order them into a digital matrix. Special software are used to fill this matrix with the appropriate category information. This task requires a lot of interaction between man and machine because it isn't possible, normally, to develop software smart enough to complete it in one pass through the data. At the

completion of this activity, the result is a digital matrix of radar return category information which is a symbolic map of the ground. Each cell in this matrix represents a specified ground spot (both location and size) and lists the backscatter category of that point. One last task remains before we have a completed ground truth data base: We must obtain digital elevation data of the scene and add it to the matrix.

Fortunately, for the data bases made under this contract, digital elevation data were provided to us by ETL (Engineer Topographic Laboratories, Fort Belvoir, Virginia). We did not have to produce the elevation data. We merely had to extract the desired data from each of the computer-compatible tapes containing data of the site and merge these data into an orthogonal coordinate system. We combined these data into one digital matrix. At this point we need only merge the digital category and elevation matrices.

We merged the digital category and elevation matrices into one four-dimensional matrix which is, then, the ground truth data base for a specified target scene. Upon completion of this activity, the ground truth data base is ready for input to the radar simulation program. It, the data base, is a digital model of the backscatter category features and elevation variations present in the target scene.

As can be seen, most of the work was performed by humans when constructing data bases. The techniques used are basically manual techniques. A photo-interpreter scans the intelligence data and draws upon his interpretation experience to decide what information to transfer manually to the data base under construction. These decisions are made with as few computer enhancements as possible. Several reasons exist to account for this: (1) Multi-useful computer enhancement routines are not generally available; (2) Use of computer enhancements causes the interpreter to lose visibility of and control over what he is trying to do. These reasons have serious portent for feature extraction and data base construction. Data are manipulated by hand and the best information is not obtained.

What is needed is a workable marriage between the computer and interpreter. The computer excels at manipulating vast amounts of data and the human is incomparable when it comes to drawing upon learning

experiences to make decisions. A cooperative approach is desired in which the human is used to make decisions and guide the processing direction of the software, and the computer is used to manipulate the data rapidly and easily and to remove the drudge from the human. This cooperative approach to data base construction is called interactive feature extraction, or automated feature extraction.

5.2 Description of Pickwick Data Bases

Two ground truth data bases have been constructed of the topographic area in the states of Tennessee, Mississippi, and Alabama for a twelve - mile square centered on the northwest corner of the Power House Building at the Pickwick Landing Dam across the Tennessee River. One for the model validation tasks and one for the reference scene generation task. Both data bases were constructed from the same source imagery and both were stored in digital matrices. The data base for reference scenes was made first and will be discussed first.

5.2.1. Reference Scene Data Base

After specification of the test site and radar system parameters, source data were acquired from which the ground truth data base could be built. Construction of the data base was separated into two halves. The first half was acquisition of elevation data which accurately modeled the relief present in the topography of the test site. The second half was construction of a feature map which accurately represented the geometry and radar return (dielectric) properties of the objects and features, natural and man-made, present in the test site.

The elevation data were provided by ETL. These data were produced by DMA (Defense Mapping Agency). DMA digitized 20 foot elevation contours for each standard 7 1/2' USGS (United States Geological Survey) quadrangle map. DMA ran an interpolation computer program on the digitized elevation contours and produced a digital elevation matrix for each map. The interpolation program calculated an elevation value in an orthogonal grid matrix for each 6.25m (20.505 feet) increment in either direction with an approximate accuracy estimated to be 10 feet. The coordinate

system used for these data was the UTM (Universal Transverse Mercator) projection which was assumed orthogonal over the small area. These digital elevation matrices were stored in a computer-compatible format on digital magnetic tapes, one tape for each map. Portions of six maps were required to cover the area included in the data base site. This means that it was necessary to merge the elevation data from six different magnetic tapes each having data stored in an orthogonal grid matrix and the orthogonal grid matrix of each being slightly askew with respect to each other. These elevation data were merged into one orthogonal grid matrix in the UTM coordinate system. The details of this merging of the elevation data are reported in Volume II¹⁹.

The feature map was constructed at RSL. It was built by standard feature extraction techniques. Standard 7 1/2' USGS quadrangle maps (1:24,000 scale) and high-resolution aerial photographs (1:100,000 scale) served as input source data for this activity. Using these source data, a photo interpreter defined the boundaries outlining homogeneous regions (homogeneous at radar wavelengths) and manually transferred these boundaries to a stable-base drafting material. Meticulous care was exercised throughout construction of this feature map to hold spatial resolution to approximately 0.05 inches on the map which, at 1:24,000 scale, corresponds to 100 feet on the ground. This 100 foot spatial resolution corresponds more to the geometry and location of gross features (features which are very obviously dissimilar at radar wavelengths) and less to separation between similar but slightly different features (at radar wavelengths). Where to draw the line about which features needed to be explicitly represented on the planimetry map (previously called feature map) and which could be grouped together in a larger, undifferentiated, region was left to the experience, knowledge, and intuition of the interpreter. The details of the feature extraction process and construction of this planimetry

¹⁹ McNeil, M., V. H. Kaupp, and J. C. Holtzman, "Digital Elevation Data Base Construction: Pickwick Site," TR 319-3, Remote Sensing Laboratory, The University of Kansas, July, 1976, Appendix C. Vol. II, ETL TR-0118.

map are reported in Volume II²⁰.

The next step was to digitize the planimetry map. This was accomplished on a large-table digitizer. The boundaries of all the homogeneous regions were digitized and these data were stored on digital magnetic tape. Devising techniques to eliminate redundancy while separately accounting for disparate regions was a major problem to hurdle while digitizing the planimetry map. After manual digitization of boundaries was completed, these data were converted into a three-dimensional orthogonal grid matrix: Two dimensions defined the position of each point on the ground and the third specified the radar return category. A radar return category is specified in this matrix for each 6.25m (20.505 feet) increment in either direction. The coordinate system used was the UTM. The resultant digital matrix was stored on digital magnetic tape. This digital planimetry map was a symbolic representation of the types and locations of radar return categories present in the test site. Many problems had to be overcome in the process of digitizing the planimetry map and constructing a symbolic category map stored on digital magnetic tape. The details of constructing this digital symbolic map are presented in Volume II²¹.

The final step required to make the ground truth data base for the Pickwick Landing Dam test site was to merge the digital matrices of elevation and planimetry data into one four-dimensional matrix²². This step was straight-forward since the preliminary activities prepared the intermediate products in the right formats. The resultant data base was stored as a digital matrix on computer-compatible magnetic tape. The details of this work are reported in Volume II. The position, elevation, and radar return category are specified for each 6.25m (20.505 feet) increment in either direction in an orthogonal grid matrix (UTM coordinate

²⁰ Davison, E., V. H. Kaupp, and J. C. Holtzman, "Baseline of Planimetric Data Base Construction: Pickwick Site," TR 319-2, Remote Sensing Laboratory, The University of Kansas, July, 1976, App. B, Vol. II, ETL TR-0118.

²¹ McNeill, M., V. H. Kaupp, and J. C. Holtzman, "Digitization of Pickwick Site Data Base," TR 319-4, Remote Sensing Laboratory, The University of Kansas, February, 1977, App. D, Vol. II, ETL TR-0118.

²² Komp, E., M. McNeill, V. H. Kaupp, J. C. Holtzman, "Medium Resolution Digitization Ground Truth Data Base," TR 319-5, Remote Sensing Laboratory, The University of Kansas, August, 1977, App. F, Vol. II, ETL TR-0118.

system). This is so even though the spatial resolution of the radar return category data is coarser than 100 feet. Several reasons exist for the data base to be structured this way. First, the range resolution of the radar system being modeled was approximately 100 feet, but it was not known whether it might be necessary at a later date to increase the spatial resolution of the category data to enhance the probability of correlation with the "live" video. Second, it was desired to use this data base for the validation tasks (Sections 2 and 3) by adding radar return category detail. For these reasons, it was decided to keep the spatial resolution of the elevation data (one point specified every 6.25m) for the ground truth data base of the Pickwick Landing Dam test site. The final data base has a spatial backscatter category or approximately 100 feet and an elevation resolution of approximately 10 feet, and was built to support the reference scene generation task (Section 4).

Photographs of the data base are presented in Figures 27 and 28. Figure 27 is a photograph of the elevation data portion of the Pickwick Landing Dam test site. In this photograph relative elevation data have been encoded to greyscale with black being the lowest point in the data base and white the highest. All other points are an intermediate shade of grey. Sixty-four (64) absolute levels of grey from black to white were present in the data which produced this photograph but not that many distinguishable shades of grey survive the several generations of copying and printing the picture has been through. However, the photograph presents a valid representation of the relative variations of relief present in the data base and attests to the accuracy of the elevation data (compare it to a map). Figure 28 is a photograph of the radar return category data portion of the data base. In this photograph, category data have been symbolically encoded into greyscale data. The photograph presents a symbolic representation of the homogeneous regions into which the test site was divided. These two sets of data (elevation and category) together comprise the ground truth data base of the Pickwick Landing Dam test site for reference scene generation.

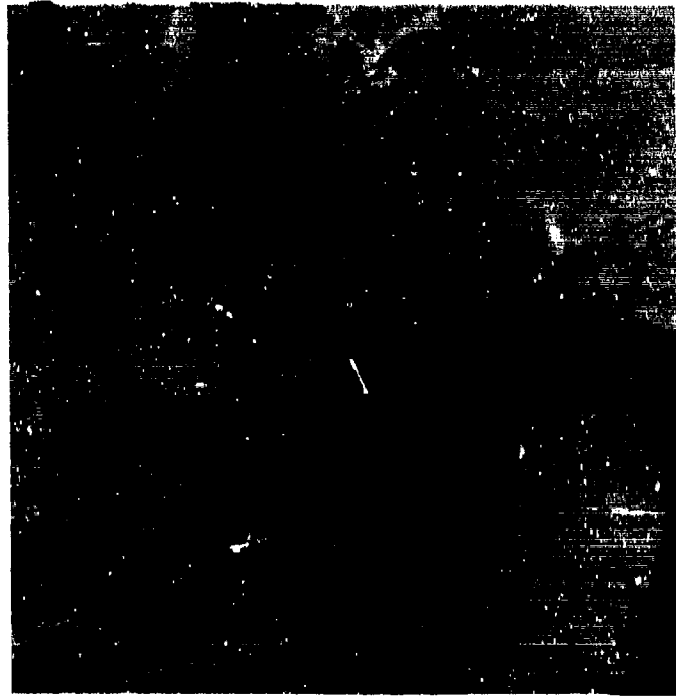


Figure 27. Planimetry map of Pickwick Site.



Figure 28. Elevation Map of Pickwick Site.

5.2.2 Model Validation Data Base

The data base prepared for the reference scene generation task did not contain sufficient resolution to support the validation tasks. The spatial backscatter category resolution of that data base (5.2.1) was, at best, 100 feet. One hundred foot resolution was too coarse. We wanted to validate the model for medium resolution (60 feet) for both SLAR (Side-Looking Airborne Radar) and PPI (Plan-Position Indicator) radars. Thus, we decided to make a validation data base by adding sufficient category detail to the previously constructed basic reference scene generation data base, thereby increasing the resolution to, at most, 60 feet. This task was made easier by the facts that the basic data base digital matrix consisted of a point for every 6.25m (20.505 feet) on the ground and the elevation data were prepared from 20 foot contours. These facts mean that the basic data base had sufficient implicit resolution to allow us to extract the additional backscatter category features from the source intelligence data (imagery) and add these data to the original data base.

The feature map (planimetry and categories within the boundaries) of these additional backscatter categories was constructed at RSL. It was built by standard feature extraction techniques. The same standard 7 1/2' USGS quadrangle maps (1:24,000 scale) and high-resolution aerial photographs (1:100,000 scale) used to make the reference scene data base served as input source data for this activity. Using these source data, a photo interpreter defined the boundaries outlining the additional homogeneous regions (homogeneous at radar wavelengths) corresponding to the desired spatial resolution, and manually transferred these boundaries to a stable-base drafting material. Meticulous care was exercised throughout construction of this feature map to hold spatial resolution to approximately 0.03 inches on the map which, at 1:24,000 scale, corresponds to 60 feet on the ground. This 60 foot spatial resolution corresponds, as in the previous data base, more to the geometry and location of gross features (features which are very obviously dissimilar at radar wavelengths) and less to separation between similar but slightly different features (at radar wavelengths). The decision of what different features were to be added to the original map (previously called feature map) was again, left to the experience, knowledge, and

Intuition of the Interpreter. The details of the feature extraction process and construction of this planimetry map are reported in Volume II¹².

The next step was to digitize the planimetry map. This was again accomplished on a large table digitizer. The boundaries of all the new regions were digitized and these data were stored on digital magnetic tape. The final step required to produce the validation ground truth data base was to merge these additional backscatter categories with the reference scene data base reported in Section (5.2.1)¹³. After manual digitization of boundaries was completed, these data were converted into a three-dimensional orthogonal grid matrix: Two dimensions defined the position of each point on the ground and the third specified the radar return category. A radar return category is specified in this matrix for each 6.25m (20.505 feet) increment in either direction. Even though a category is specified in the matrix for each 6.25m on the ground, it should be remembered that the spatial resolution of specification of backscatter categories was designed to be, at most, 60 feet. These data were then merged with the original 100 foot data base to make a new 60 foot data base for the validation tasks.

This task of merging was very difficult because of several complicating factors. First, precise geometric registration, given the normal drafting and hand digitizing tolerances, was difficult to achieve. Second, frequently the new category data completely re-arranged boundaries in certain areas. This occurred because, when sub-dividing a region according to 60 foot resolution, instead of 100 foot resolution, the entire category organization was changed. This alteration of a 100 foot data base to a

¹² Davison, E., V. H. Kaupp, J. C. Holtzman, "Increased Resolution of Planimetric Data Base: Pickwick Site", TR 319-21, Remote Sensing Laboratory, The University of Kansas, March, 77, Included in Appendix E, Vol. II, ETL TR-0118.

¹³ Komp, E., J. L. Abbott, V. H. Kaupp, J. C. Holtzman, "Improved Resolution Digital Ground Truth Data Base: Pickwick Site", TR 319-23, Remote Sensing Laboratory, The University of Kansas, August, 1977.

60 foot data base was not just the simple task one might imagine of adding sub-divisions within major divisions. Third, because of the additional category complexity in the new data base, many more instances occurred of a single boundary point separating three, and even four, different categories. These complications, plus the very large number of data points in the data base, all combined to require that much extra effort had to be devoted to the design of the merge software.

The resultant data base had a spatial backscatter category resolution of, at most, 60 feet, elevation accuracy of approximately 10 feet, and was built to support the validation tasks performed under this contract (Sections 2. and 3.). It was stored in a digital matrix on computer compatible magnetic tape.

5.3 Source Intelligence Analysis

Another goal existed for construction of data bases for this study: Evaluation of alternate input data sources and identifying construction time and problems. To accomplish the first part, two versions of a data base were built. One version was constructed using only optical photographs and topographic maps for the input intelligence data. The other using only radar images (for category boundary determinations) and topographic maps. The second part of the goal (construction time and problems) was accomplished by keeping appropriate records and documenting the problems.

5.3.1 Optical Intelligence Data

High resolution aerial photographs and topographic maps were used to construct a data base containing 100 foot spatial resolution of backscatter data of the Pickwick Landing Dam site for the reference scene generation task (Section 4.). Construction of this data base required the following time:

*Feature Extraction	43 hours
Digitization	23 hours
**Digital Matrix Preparation	288 hours
**Elevation Data Merge	132 hours
Category and Elevation Data Merge	6 hours
Total Time	492 hours
*Includes 15 hours preparation time and 28 hours feature extraction time.	
**Includes Software Development Time	

The details of this work and problems encountered have been separately reported 19, 20, 21, 22.

- 19 McNeill, M., V. H. Kaupp, J. C. Holtzman, "Digital Elevation Data Base Construction: Pickwick Site", TR 319-3, Remote Sensing Laboratory, The University of Kansas, July, 1976. Included in Appendix C, Vol. II, ETL TR-0118.
- 20 Davison, E., V. H. Kaupp, J. C. Holtzman, "Baseline of Planimetric Data Base Construction: Pickwick Site", TR 319-2, Remote Sensing Laboratory, The University of Kansas, July, 1976. Included in Appendix B, Vol. II, ETL TR-0118.
- 21 McNeill, M., V. H. Kaupp, J. C. Holtzman, "Digitization of Pickwick Site Data Base", TR 319-4, Remote Sensing Laboratory, The University of Kansas, February, 1977. Included in Appendix D, Vol. II, ETL TR-0118.
- 22 Komp, E., M. McNeill, V. H. Kaupp, J. C. Holtzman, "Medium Resolution Digital Ground Truth Data Base", TR 319-5, Remote Sensing Laboratory, The University of Kansas, August, 1976. Included in Appendix F, Vol. II, ETL TR-0118.

The quality of the resultant data base is best described by the results produced in the task for which it was prepared: Reference scene generation for terminal guidance applications (Section 4.0). Preliminary results of the tests performed on that task indicate that the data base and resultant simulations satisfied or exceeded requirements. Two additional comments can be added to embellish the comments regarding the apparent quality of the data base. First, input optical intelligence source data seemingly have good quality geometric fidelity, attested to by the preliminary results of the Correlatron tests (geometric fidelity is believed to be important for the Correlatron) as reported in Section 4.0. Second, these source data apparently provide sufficient intelligence for a reasonably knowledgeable photo-interpreter to extract valid backscatter category features, again attested to by results.

5.3.2 Radar Intelligence Data

Radar imagery and topographic maps were used to construct a data base containing 100 foot spatial resolution of backscatter data of the Pickwick Landing Dam site for the reference scene generation task (Section 4). The radar imagery were taken by a Goodyear APD-10 Synthetic Aperture Radar (see Section 2., for more information). Construction of this data base required the following time:

Feature Extraction	47 hours
Digitization	21 hours
*Digital Matrix Preparation	276 hours
*Elevation Data Merge	132 hours
Category and Elevation Data Merge	<u>6</u> hours
Total Time	482 hours

* Includes Software Development Time

Again, it should be noted that the radar imagery were used to outline boundaries (feature extraction) between various radar backscatter categories. Radar imagery were not used as sources of backscatter data or greytone to be used in later simulation activities. The data base has been constructed, but it has not yet been tested by using it for input to produce simulated reference scenes for testing on the Correlatron. These reference scenes will be produced a little later and these results can be updated to

assess the quality of the data base as inferred by results of the Correlation tests.

Some problems were encountered in making this data base which will be discussed here, since they have bearing on similar future activities. We began the development of this data base with one goal in mind: To determine the feasibility of constructing a data base using only radar imagery as the source intelligence data. We concluded rather rapidly that, without the aid of a digital computer for rectification of geometric distortions, this would not produce a very accurate data base having the desired geometric fidelity. The data base we did construct used topographic maps in addition to the radar imagery as the source intelligence data. It is this data base we are waiting to test.

A summary of our brief study of the geometric fidelity of the source radar imagery follows.

Several methods were used to enlarge the radar imagery (from 1:100,000) to the appropriate scale (1:24,000) so that the planimetric information could be transferred. The first method consisted of constructing a grid on an acetate-based tracing medium. A corresponding grid was constructed on the imagery and used as a reference in aligning the imagery and preventing rotation as the imagery was enlarged on a transfer scope. Although the grid facilitated transfer of the planimetry, the finished planimetric map clearly did not register when compared with a U.S.G.S. topographic map of the same area. The imagery was then enlarged photographically with a transparency being produced at the same scale as that of the U.S.G.S. map (1:24,000). Once more it was clear that significant geometric distortion was present in the imagery which did not allow even approximate registration with the map.

We then decided to measure the variations which were found between radar imagery and map. This was accomplished by selecting a number of bench marks on the map, the locations of which could be either positively identified (such as road intersections) or inferred with a high level of confidence (a few meters). Transects were then drawn between the bench marks on the map and measured. Photographic enlargements of the radar imagery were made at the same scale as the topographic map, with the four prints needed to cover the area being used to construct a mosaic. The geometry

of the mosaic in relation to that of the original image was not subject to distortion since the negatives used in the printing were taken from two adjacent image strips (APD-10, Channels A and B of the same pass) and were easily matched.

The distances along transects between bench marks on the topographic map were measured and compared with those on the enlarged mosaic. Table 4 lists the various distances and the percentage of error represented.

TABLE 4.

<u>Bench Mark Number</u>	<u>Map Distance</u>	<u>Image Distance</u>	<u>Error</u>	<u>Major Direc- tional Trend</u>
1. PSR 7L - PSR 4L	17.05	16.5	3.2%	Range
2. PK4 - L171	15.8	15.8	0	Azimuth
3. S155 - Q155	12.7	12.2	3.9%	Diagonal
4. PSR 4R PSR 2R	15.3	15.3	0	Azimuth
5. PSR 2L - PSR 2R	6.6	6.55	1.32%	Diagonal
6. PK4 - T155	11.7	11.5	1.7%	Diagonal
7. PSR 7L - N155	10.1	10.1	0	Azimuth
8. PSR 7L - PSR 4R	21.85	20.6	5.7%	Range

There are several possible sources of error preventing use of this APD-10 imagery for mapping. The first of these is image compression in either the range or azimuth direction. The common causes of such compression in ground range systems are layover in the range direction and inexact synchronization between the SLAR recording equipment and the ground speed of the aircraft in the azimuth direction. It has been noted²² that problems

²² Dellwig, L. G., B. C. Hanson, N. E. Hardy, J. C. Holtzman, P. L. Hulien, J. R. McCauley, and R. K. Moore, "A Demonstration and Evaluation of the Utilization of Side Looking Airborne Radar for Military Terrain Analysis," RSL Technical Report 288-1, October, 1975. Supported by U. S. Army Contract DAAG02-75-C-0145.

of foreshortening and layover become more severe with increasing magnitudes of relief. The local relief in the Pickwick area averages 100 to 150 feet with some elevations north of the lake reaching nearly 300 feet above lake level. In examining the transects between bench marks, the extent of intervening relief was considered.

The first transect examined extends predominantly in the range direction. Although both bench marks lie approximately 30 feet above water level and within 1 foot of each other in elevation, bluffs up to 120 feet higher than the bench marks (150 feet above lake level) appear along the entire length of the transect. The error in this case was 3.2%. Conversely, the second transect lies predominantly in the azimuth direction. The elevations of the two bench marks are within 4 feet of each other. There are no intervening topographic features and no difference between map distance and photo distance is apparent. The third transect, lying in a diagonal direction between range and azimuth, has the second highest error with 3.9%. Elevation differences of up to 60 feet occur along the transect. The remaining transects, with one exception, show very minor errors or no errors. In each case, the bench marks are within 10 feet of each other in elevation and usually extend directly across the water. The one exceptional case is a transect which extends for the greatest measured distance, and is in the range direction. This transect showed the highest error (5.7%) with 26 feet of elevation difference between the bench marks.

Based upon the major directional trends of the transects, elevation differences between bench marks, and topographic features in the area, it would appear that the major source of planimetric error in the APD-10 imagery is compression in the range direction related, at least in part, to the hilly topography. Thus, it was concluded, that the geometric fidelity of this imagery was insufficient to support mapping efforts, and that topographic maps were needed (or, of course, aerial photographs) to satisfy data base geometric fidelity requirements. This means that the greatest benefit of using radar imagery to make data bases would come in the feature extraction task; deciding which backscatter categories to include in the data base.

5.3.3 Source Data Analysis Results

In general, we have concluded even without completing the test, that the test data base would be built using as much input source intelligence data as possible. These include optical high-resolution aerial photographs, IR (Infra-Red) imagery, radar imagery, topographic maps, etc. The maps and aerial photographs would be used primarily for geometric fidelity and the IR and radar imagery would be used primarily for backscatter category discrimination. The closer the resolution, frequency, polarization, etc., is of the radar imagery to the system being simulated, the better the data base in the sense that identification of the right category boundaries would be enhanced.

For data bases constructed using either optical photography or radar imagery, we concluded that the optical photography was the better source material for the principle reason that geometric distortion was minimized. Geometric distortion in radar images presents a real problem for mapping which must be treated. We also concluded that the total time required to construct data bases was approximately the same, regardless of whether optical or radar source data were used.

5.4 Interactive Feature Extraction

5.4.1 Background

Manual techniques get the job done, but are not time or cost-effective. Because of this, they restrict the usefulness of radar image simulation. The increased usage of radar image simulation to solve present and future problems is, therefore, dependent, in part, upon automating the problems of ground truth data base construction. Most all of the problems of ground truth data base construction are involved with identifying the geometric and electromagnetic (location, elevation, orientation, and backscatter category) properties of the scene which are to be transferred from input source intelligence information to the data base. This process is called feature extraction. Therefore, the problem of automating the ground truth data base definition is really analogous to automating the feature

extraction process. Clearly, such a development would result in a tremendous improvement in data base construction and hence in radar image simulation.

Given the problem of expediting the data base construction process and its background, solutions to this problem were investigated. As noted, the data base construction problem is, basically, the problem of feature extraction. A definition of feature extraction given by Patrick²⁴ is: "Feature extraction is the reduction of a set of measurements containing a relatively large amount of data into a smaller amount of information (features)." Clearly, this is the task that lies at the core of data base construction, as the initial set of data (maps, photographs, etc.) contains a large amount of data but a smaller amount of useful information (categories), and the task is to define those categories (i.e., convert the initial data to a set containing a smaller amount of features). Manual techniques of feature extraction have been used in the past, but all manual techniques suffer the same fault - they are time-consuming and costly. This is so because of the very nature of the techniques; they are manual, and hence performed by hand, which due to the limitation of human endeavors naturally imposes a limit of how fast, accurate, and effective they can be.

Therefore, our only hope in expediting the feature extraction process is to automate it. The computer is many orders of magnitude faster than a human when it comes to certain tasks. For instance, the computer is very good in manipulating vast amounts of data and "number-crunching" in a short period of time, whereas the human is not. The computer is better than the human when it comes to performing repetitive tasks, statistical analysis, image enhancements, and other clearly defined operations. If the computer is so much better than the human at these things, then one would naturally expect the computer to completely take over these tasks. Thus, the best situation would seem to be that the computer completely automate the feature extraction process, making it a much faster, more

²⁴ Patrick, Edward A., Fundamentals of Pattern Recognition, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1972.

cost-effective, and less error-prone process. However, this solution doesn't work. Granted, the computer can perform many of these feature extraction processes better and faster than the human, but it lacks one thing - intelligence. The computer is not smart enough to guide itself through an image and accurately extract features. It does not have the experience, knowledge, learning and decision-making capabilities of a human. Thus, a fully automatic feature extraction system is not feasible²⁵.

5.4.2 Combining the Computer and the Human

Since previous studies indicate that neither the human nor the computer, by themselves, are optimal at the task of feature extraction, an investigation into combining the human and the computer into a workable system was undertaken. This investigation explored the concept of a marriage between the computer and the human in which the human is used to make decisions and guide the system, and the computer is used to manipulate the data and handle other chores which would otherwise place a burden on the human. An attempt has been made to tune such a system so that the human performs whatever functions he does best and the computer performs the functions it can do best. In this way, the maximum return can be gained through a minimum of time and effort on behalf of both the human and the computer. This cooperative approach is called interactive feature extraction, since the human interacts with the computer in order to extract features, or alternatively it is called automated (not automatic) feature extraction, in that the computer is automating as much of the feature extraction process as possible.

In interactive feature extraction, the computer is used to display, enhance, manipulate, and otherwise aid the human interpreter as he performs his function. Viewed another way, the human is used to make decisions and to guide the computer in real-time as the programs run. Interaction can be accomplished by giving the interpreter a few basic tools with which to

²⁵ Frost, V. S., J. L. Abbott, V. H. Kaupp, and J. C. Holtzman, "Investigation of an Interactive Approach for Radar Simulation," TR 319-15, Remote Sensing Laboratory, The University of Kansas, March, 1977. Included in Appendix K, Vol. II, ETL TR-0118.

communicate his decisions to the computer; a keyboard for commands and joystick for direct specification are probably the minimum to be provided. Given these capabilities, the data base can be built directly as the feature information is processed and decisions are made. Boundaries separating different regions can be specified directly by the interpreter and, while the human is analyzing the next problem area, the computer can build the symbolic data base immediately and display the results. Depending upon the level of sophistication of the interactive software, and the computer and display complex, tremendous savings of resources and improvements in efficiency and quality of the finished product are visualized. Given an interactive feature extraction system, special emphasis could be built in to maximize the use of the intelligence data normally available from which to define the geometry, dielectric properties, and elevation data required to be included in a data base for radar image simulation.

A typical session using an interactive feature extraction system to build a data base would probably look like this: First, the input maps, photographs, imagery, and other information sources will be entered into the system by means of some analog-to-digital converter. This input will form the initial data files. The operator then will log on to the computer and call the interactive feature extraction system. Now, the operator will decide which input images he wants to view and transfers them to the viewing screen. Then, if there are any automated routines (e.g., cluster packages, gradient operators, etc.) that he wants to run on the images, he will run them and transfer the results to the viewing screen. Now he is ready, using the joystick or light pen and the keyboard to transmit commands to the system specifying which manipulations are to transform the input data into the data base to start interacting with the computer. While the operator is guiding the system, the computer is performing the manipulations indicated and returning results to the operator in semi-real time. When the operator is finished creating the data base, he saves the final image in permanent storage and signs off the system, his job completed.

Using such a conceptual interactive feature extraction system as functionally described above, the process of data base construction could be speeded-up tremendously. No longer does an intermediate hand-drawn map

have to be constructed since the input data are accepted by the computer as is. The manual digitization step is no longer needed, as digitization is done by the computer guided by the Interpreter and his light pen or joystick. The reconstructive computing performed on the digitized data is also eliminated, as those steps are integrated into the computer's line-following and region-defining routines. Thus, all that is needed is the system, the input intelligence data, and the operator, alias photo/radar/imagery Interpreter. Interactively, a large, complex data base similar to the Pickwick Dam data base could be built in several multi-hour sessions as opposed to several months by the manual construction method. Clearly, this is a tremendous savings in time and effort. Given that obtaining data bases for radar image simulation is a worthwhile effort, the proposed interactive feature extraction system would be a very powerful tool to the radar image simulation process.

5.4.3 Use of System In Data Base Update

Besides facilitating feature extraction for data base construction, an interactive feature extraction system would prove to be a very useful tool in other areas of radar image simulation. An area in particular that would be enhanced by the introduction of such a system is the periodic updating of existing data bases to reflect changes in the ground scene. Such updates are necessitated by changes in the ground scene due to such factors as seasonal variations (trees, foliage, and crops changing), meteorological changes (presence or absence of snow, rain, etc.), and other events which alter the ground scene sufficiently to affect the radar image. In many applications (especially military applications), the updating of radar image data bases will play a vital role. For instance, if the radar image simulation is being used as a reference scene for a terminal guidance device, and several hours before use the target scene is covered with eight inches of snow, the data base and reference scene must be updated to accurately reflect ground conditions. In such a situation where the radar image simulation is being used to model a dynamic environment, there must exist a fast method to update the data base. Once again, the interactive feature extraction system could be

effectively used to solve the problem. Using the system, an operator in a short time using updated Intelligence could easily examine the data base and alter it to match the situation by merging, expanding, or contracting regions, changing boundaries, and altering the categories or contents of the data base.

5.4.4 General Specifications

In order to create such an interactive feature extraction system as conceptualized above, certain physical requirements must be fulfilled. The following minimum physical requirements have been identified. First of all, since this is a computerized system, some hardware configuration (i.e., computer) must be at the core of the system. The basic requirements in this area are processing power, main memory, auxiliary storage, I/O (Input/Output) capability and supporting peripheral devices, and a basic software operating environment. Included in this area would be a terminal by which the operator could communicate with the computer. Another physical requirement is for some form of display capability. Since the system is intimately involved with images, there must be some way to display these images. Some physical devices which would provide a display capability include television monitors, graphic terminals, plotters, film recording and oscilloscopes. Associated with this display is a very important part of the system: The interactive link between the displayed image, the operator, and the computer. The operator must have some way of extracting information from images. Several means to accomplish this are a light pen, joystick and cursor, or a cursor with simple x, y controls (etch-a-sketch type controls). These devices allow the operator to access desired regions on the image and selectively extract features. All of these devices define the minimum physical configuration needed in order to implement an interactive feature extraction system. This subject is discussed in more detail elsewhere.²⁶

²⁶ McNeil, M., J. L. Abbott, V. S. Frost, V. H. Kaupp, J. C. Holtzman, "Automated Techniques in Feature Extraction," TR 319-24, Remote Sensing Laboratory, The University of Kansas, June, 1977. Included in Appendix L, Vol. II, ETL TR-0118.

5.4.5 Rationale For Interactive Data Base Construction

The single most persuasive factor in the selection of the feature extraction system was the need for interactive capability. Manual techniques were investigated and found to be time-consuming and cost-ineffective. Fully automatic techniques were investigated and found to be non-existent, for the most part. Although some automatic techniques do exist, they are useful only in very specific applications and work only with certain types of carefully chosen data. Thus, the human operator and the computer have to work together in some fashion in order to form a workable system.

The ideal system would be to have the computer doing all of the work, with the human inside the loop providing guidance. In any such man-machine system, how well the system works is dependent upon the ease of interaction between the computer and the operator.

This area has been looked into with special emphasis on applications of interactive processing to radar image simulation. Results of that investigation are reported elsewhere²⁵. The end result of that investigation was to recommend the interactive approach to radar simulation as the most promising general solution to the problems associated with radar image simulation, including the data base construction and updating process.

Another area of study impacting on the development of a feature extraction system is a study of techniques used in analyzing and interpreting images. Since the purpose of this feature extraction system is to facilitate this process, it makes sense to study in detail the process that the system will be attempting to perform. A study on image interpretation techniques has been undertaken and is reported in detail elsewhere²⁶. Current image analysis and interpretation techniques are studied, with emphasis on both the tried-and-true manual techniques and some of the

²⁵ Frost, V. S., J. L. Abbott, V. H. Kaupp, and J. C. Holtzman, "Investigation of an Interactive Approach for Radar Simulation," TR 319-15, Remote Sensing Laboratory, The University of Kansas, March, 1977. Included in Appendix K, Vol. II, ETL TR-0118.

²⁶ McNeil, M., J. L. Abbott, V. S. Frost, V. H. Kaupp, J. C. Holtzman, "Automated Techniques in Feature Extraction," TR 319-24, Remote Sensing Laboratory, The University of Kansas, June, 1977. Included in Appendix L, Vol. II, ETL TR-0118.

newer automated and interactive techniques. Some of the manual techniques previously used on this project are reported in [26]. Also discussed in [27] are some of the ways that the proposed interactive feature extraction system could be used in interpreting images, both by automating older methods and by creating new feature extraction methods specifically designed for the system.

The two salient features of the proposed system are, (1) the introduction of the human and his subsequent interaction with the system and (2) the use of the computer to automate the feature extraction process. As mentioned before, a fully general automatic feature extraction system does not exist, but that of course does not mean that certain automated techniques do not exist. In fact, many useful automated techniques do exist. A brief survey of automated feature extraction techniques has been made²⁵. One of the favorable points about the feature extraction system is that it will bring together many of these routines and spark interest in the creation of more automated feature extraction techniques. The operator will then have at his immediate disposal the use of all these routines to assist him in extracting information.

Implicit in all this discussion about feature extraction is that there is an image (or images) which has features to be extracted. In fact, the entire feature extraction system is really just a specialized image handling system. As such, the system must deal with many different problems which are connected to image handling and processing. The major areas of concern are the storage and retrieval of images, transfer time to and from auxiliary storage, main memory and display devices, management of images, and manipulation of images. All these areas involve some special problem or problems peculiar to image handling and processing that need to be addressed in the design of any image handling system.

²⁶ McNeill, M., J. L. Abbott, V. S. Frost, V. H. Kaupp, J. C. Holtzman, "Automated Techniques in Feature Extraction," TR 319-24, Remote Sensing Laboratory, The University of Kansas, June, 1977. Included in Appendix L, Vol. II, ETL TR-0118.

²⁵ Frost, V. S., J. L. Abbott, V. H. Kaupp, and J. C. Holtzman, "Investigation of an Interactive Approach for Radar Simulation," TR 319-15, Remote Sensing Laboratory, The University of Kansas, March, 1977. Included in Appendix K, Vol. II, ETL TR-0118.

5.4.6 An Interactive Feature Extraction System: A Design Concept

The concept of an interactive automated feature extraction system has been investigated, and some of its possible uses in the radar image simulation area explored. Having studied the problems to be tackled and the utility of such a system, it has been decided that an interactive feature extraction system is a valid effort towards solving some of the problems of radar image simulation. Initial design considerations have been studied,²⁷ and that work is reported below. It should be noted here that this design concept is only a first attempt using very limited hardware. The main purpose of this effort is to design a base skeletal system limited to the hardware available, and then to see if the concept is valid enough to implement a full-scale version.

Here at the RSL, the following computer hardware and software is available for use in the implementation of the interactive feature extraction system. The heart of the system will be a Digital Equipment Corp. PDP-15 model 20. The PDP-15 is an 18-bit minicomputer with 32K of memory. It has a card reader, paper tape reader and punch, two printers, two CRT's, one TTY, four DEC-tape drives, and two removable pack disk drives. It is interfaced to an IBM 7094 to provide regular magnetic tape drive capabilities. The PDP-15 is also interfaced to a hybrid system, the Image Discrimination Enhancement Combination System, or IDECS. The IDECS is used basically as an image transfer and display device, although it has other capabilities.³⁰ A high-resolution monitor ($\geq 1K \times 1K$ pixels) will be used as the main display device, with an analog memory refreshing the monitor.

The interactive feature extraction system is designed to be run as a single-user sub-system under DOS, the disk operating system on the PDP-

²⁷ Anderson, P. N., et al., "Image Processing with a Hybrid System: The IDECS," The Bulletin of Engineering No. 64, University of Kansas Publications, Lawrence, Kansas, 1972.

15. Thus, the feature extraction software is one level removed from the hardware. This fact does not really restrict the system, but allows it to use already existing code in the operating system. Future implementations may choose to design the system to run as a stand-alone system not using the vendor-supplied operating system for reasons of efficiency and speed, but at this level of implementation, efficiency is not as important as the extra work involved. It is also possible to design the system to operate in a multiple-user, or time-shared, mode, but again the utility gained is not worth the extra work. Besides the basic extra work it would take to design the system in these other ways, there are hardware constraints, such as available memory, which influenced the decision to make the system a single-user sub-system.

The basic input to the system will be images in the form of maps, negatives, pictures, etc. Of course, these are not in a form usable by the computer. Thus, the system will have an analog to digital converter which will convert these inputs to a digital form. These inputs will then be stored in the file system, which will be on disk. Also, the data base and other outputs will go back into the file system. See Figure 29 for a schematic block diagram.

As mentioned before, one of the two salient features of the system is its use of automated routines. The automated feature extraction routines have, for the most part, been left vacant to be added on to the system at a later date. In this way, emphasis on the types of automated routines is deferred until the need for them actually arises.

The other salient feature of the system is its interaction with the operator. This interaction is really the crux of the system, since the computer and the operator need to interact very closely. To accommodate this interaction, a command language has been developed by which the

operator can communicate his wishes to the system easily. This language, or menu, of interactive commands was designed with the emphasis on the user's ease of operation. Another interaction that occurs is communication between the operator and the computer regarding the location of points within an image. This interaction would ideally take place by means of some semi-hardware implemented tool like a joystick and cursor. Such a device would provide a very fast and effective way to direct the extraction of features from imagery. However, for this design, at least initially, there does not exist any such hardware, so instead there will be a cursor (or bouncing ball or framer) which will be completely software controlled. That is, in the command language will be commands which will manipulate the cursor and move it around. We realize that this will impose severe restrictions on the utility of such a system, but there is no other choice available at this time.

5.4.7 Conclusions and Recommendations

When this initial design is implemented, it will provide the bare minimum of capabilities needed to support an interactive feature extraction system. Even though it may be a slow and clumsy system at first, the concept of interactive feature extraction will be validated by using the system to create a data base of, for instance, the Pickwick Dam site. This data base will then be compared to the old data base which was created using only manual techniques. This analysis will determine if the quality of the data base created by using the interactive feature extraction system is comparable or even superior to that of the manually created data base. Also, the time and effort spent will be compared against that used in the construction of the manually created data base. Thus, there will be two criteria for determining the utility of the system: (1) quality of finished product; and (2) time, effort, and money spent in the creation of the final data base.

After this initial validation of the system, attempts will be made to upgrade the system. One area of improvement will be the addition of

functional routines. Improvement in the system-level software will be minimal, as the skeletal design should be complete. Hardware upgrading is the area where the most work needs to be done. First on the list is the need for a better interactive tool. A hardware implemented cursor or some other display cursor would result in immediate upgrading of the system, as the present software simulated cursor is just a stopgap measure. Present indications are that much of the operator's time will be spent positioning the cursor to various features on the display screen. The present method will be slow and not as dynamic as it should be. Another area of system upgrading will be providing better display capability and faster transfer times. It is anticipated that transfer times to the display and back will be slow, thus bottlenecking the system. Another area of improvement is dependent upon the usage of the system. If the system is heavily used and many files (images) are created, disk storage must be improved (such as magnetic tape storage instead of disk) or additional disk packs and drives must be added on to the system.

An alternative to upgrading the system might be to move the whole system to a new hardware configuration or a different operating environment. A multi-user operating system, RSX, is currently being tested on the PDP-15. One possible change to the system might be to change it to operate in RSX, thus allowing other users access to the PDP-15 at the same time that the system is running. In case of movement to a new hardware configuration, the changeover will be made easier because of the modular, subsystem structure of the system. Also, most of the software will be written in ANSI FORTRAN, which is easily transportable between machines.

6.0 Conclusions

The point scattering radar image simulation model and its software implementations have been verified in the work reported in this document. The model rigorously treats as a closed system the properties of the radar system being modeled, ground scene, and image medium. It mathematically expresses the relationships and interrelationships between these various aspects of the closed system. Implicit in this model are all the normal radar effects such as layover, shadow, range compression, etc. These and similar effects depend entirely upon the software implementation for accurate realization. As the validation results show, the model, its software implementation, the ground truth data bases and feature extraction techniques, and the use of empirical σ^0 data to model the radar return from the ground, have seen the science of radar image simulation make the transition with this work from an interesting research problem to an engineering tool available for many different applications. The opportunity should not be lost to extend the results obtained here by applying our radar simulation model to solve present and future problems as they occur. Although the results obtained in this work have been superior to early expectations (it was not at first thought that this much work could be accomplished in the contract period) some qualifications of those results need to be discussed. These discussions are listed in the following sections.

6.1 Reference Scene Generation

The results reported for this task are preliminary results. Tests have not been completed. Even though preliminary indications are that the reference scenes produced by our radar simulation model meet or exceed the criteria for degree of correlation, location of the correlation peak, and repeatability, remember that these results have been produced by reference scenes formed from one altitude of one data base of one test site, and the simulation model was structured to represent one PPI (Plan-Position Indicator) radar and Correlatron system.

One set of test conditions like this does not represent exhaustive testing, although, the preliminary results warrant much more enthusiasm than a single set of test conditions normally might. This is so because even though we produced reference scenes for essentially one set of test conditions (five different scenes having different resolutions were, however, produced), there were many sets of "live" PPI data available from many different approaches for this one site. Thus, our reference scenes were tested against many different radar/ground scene systems. This knowledge considerably strengthens our acceptance of the results.

6.2. SLAR and PPI Validations

The results reported for these tasks were subjective comparisons of our simulated radar images to real images of the same site. Just as do all subjective evaluations, they appeal to the viewer's interests, experience, training, and intuition for acceptance.

Two swaths having different look directions, taken from one data base, were simulated for hypothetical medium resolution (~60 foot resolution) radars having ideal operating characteristics. These simulations were then compared to real imagery of the same swaths having the same look directions but having 10x15 foot resolution. The comparisons look good, but, on their own merit, the validations are weak. One data base site for simulation and one set of comparison imagery from one high resolution radar do not represent exhaustive tests.

These results together with the reference scene results represent a much stronger validation of our model and simulation technique. The reference scene test was a quantitative validation of our model. It consisted of measuring the degree of cross correlation between our radar image simulations and "live" PPI data of the same site. The preliminary test results of this task indicate repeatable performance that meets or exceeds the test criteria which can be interpreted as quantitative validation that our radar image simulations are very much like real images of the same site. Thus, this quantitative validation substantiates the more subjective comparisons appealed to for SLAR and PPI validations.

6.3 Data Bases

The results obtained in the work performed under this contract argue more eloquently than any other debate for the quality of data bases produced. However, it should be noted that the construction techniques used are not the only valid methods of feature extraction. Equally good, or better, or worse, data bases might have been produced by utilization of different techniques. We selected our techniques. They served us well. We reported our methods and results.

6.4 Optimal Choice of Source Intelligence for Data Base Construction

Even though all results reported here were simulations formed from data bases constructed using optical photography and maps for source data, it is inferred from our work that superior results could be achieved using many different kinds of source imagery. Some examples of these kinds of source imagery might be high-resolution aerial photographs, maps, radar images, infra-red images, etc. These source imagery would be used in the feature extraction task to identify boundary locations separating different microwave backscatter categories.

6.5 Interactive Feature Extraction

Although the results obtained in this work have been shown to be outstanding, they might have been produced in a more cost effective manner. One approach to accomplishing this goal, we propose, is interactive feature extraction; an optimal combination of photo-interpreter and computer for data base construction. As we believe our radar simulation model has opened the door for many future applications of radar simulation, so do we believe that interactive feature extraction is a necessary and viable part of that future.

Whether implemented as a complete interactive feature extraction (photo-interpreter) station or as a much smaller first step, if radar image simulation is to be a part of the future, interactive feature extraction is essential. Work must be started without delay on this thaumaturgical system.

6.6 Backscatter Data

For all the radar simulations we have produced, we have used empirical backscatter data (σ^0) or theoretical scattering studies to model the radar return from terrain. We have not used radar imagery of any site as a source for either σ^0 or greytone data. These data have been exclusively taken from both RSL's empirical σ^0 data bank and the literature. Our choice for σ^0 data for any category in any simulated radar image, can be questioned. If it is, we can probably offer 3 or 4 more data sets which might have been used in lieu of the questioned set. For instance, if it had been possible to collect extensive ground truth data in the Pickwick vicinity, we might have found a particular level of moisture content suitable for certain types of vegetation. This knowledge would have been factored into the choice of σ^0 data which is stratified by frequency, polarization, season, moisture content, etc. As is normally the case with hindsight, it is possible to criticize the relative greytone on a field-by-field basis.

6.7 Related Areas of Application

The Point Scattering Model (PSM) for radar image simulation and the implementations presented (SLAR, PPI, etc.) are by no means limited to the application of terminal guidance described herein. In fact, the PSM is general and its implementation can be re-structured at any stage to account for system or terrain changes.

As an example of alternate employment of the PSM, consider the investigation of temporal changes on a target terrain scene, in particular, the seasonal changes and corresponding effects on backscatter response. The proposed alteration of the scene could affect correlation of a reference scene and actual imagery.

Radar system studies are greatly facilitated with the PSM because it is possible to predict through the visual results of simulation an optimum set of system parameters (e.g., frequency, polarization, resolution) for an imaging radar system which will produce imagery with a

maximum information content. The type of information desired would be determined by the military application of the imagery. Not only is it possible to experiment with frequency, polarization, etc., but also the transfer function of the radar receiver may be experimentally adjusted to observe the effects on imagery which may be, for instance, an enhancement of certain topographic features.

The degradations in radar imagery caused by aircraft instabilities may be observed through affects in simulated imagery by implementing yaw, pitch and roll errors into the flight parameters. Also, erratic altitude changes (with respect to mean sea level) can be easily programmed. This type of sensitivity study could show how much instability can be withstood with only tolerable adverse effects on the information content of imagery.

It has been attempted to clarify that SLAR does not imply a real aperture radar in the context of this report because with the current capabilities, we believe we can extend the PSM to account for Doppler processing, and therefore improve azimuth resolution by building the synthetic array. SAR studies will certainly be widely used for many military applications, and it may be advantageous to be able to simulate the corresponding image products for system design, terrain analysis studies and guidance.

Numerous related, additional areas of application exist for the knowledge that has been gained in performing the research leading to the results reported in this document. No attempt is being made here to generate a complete list of potential applications. Rather, we would like to expand the major conclusion that our radar image simulation model has been validated and is available for application to many different present and future problems.

7.0 RECOMMENDATIONS

The purpose of this section is to present briefly a set of recommendations which represent our thoughts on possible future courses of action. We firmly believe that the successful validation of the point scattering method (PSM) of radar image simulation is the state of the art in radar image simulation, at least for distributed targets for medium to large resolution imaging radars (We will have more to say about "fine" resolution systems later.). The point scattering method completely and exactly accounts for the transmitting/receiving system, the target/sensor interaction and the display medium. Nonetheless much work remains in merely making the implementation "operational." Furthermore, logical extensions of the point scattering method, alternate approaches for cultural or hard targets and certain related activities, should be pursued in order to bring the full weight and impact of radar imaging simulation to bear on the problems of the defense community.

This section will attempt to look ahead four or five years outlining the needed studies and activities that are required to fully develop the potential of radar image simulation. Within this framework, a set of near term goals will then be outlined. It is of particular importance to note that potential applications of radar image simulation have barely been tapped. While reconnaissance systems (direct use of simulation for reference), system synthesis, and analysis (little used up to now) are obvious applications, there are a host of other applications that are waiting; for example, change detection, and prediction of terrain conditions are just two that come readily to mind. Now that imaging radar can be simulated to within the same fidelity as that obtained by real systems, the studies suggested below can indeed make radar image simulation a very valuable mechanism for the solution of many problems.

7.1 Long Range Goals

The point scattering method has been shown to be a successful tool for producing simulated radar imagery. A specific example (a terminal guidance system) was modeled by specializing the general PSM model with

great success. The specialization was seen to be mandatory both from a technical as well as a cost effective point of view. However, in the study it was impossible to model exactly the system since very little information was provided. While this improves the confidence in the general model, better results are possible with more specification. Hence an important goal is to specify and simulate completely a system for a given application where both analysis and synthesis (the ultimate use of any simulation) can be fruitfully employed in the design, development and deployment of a reconnaissance system be it for guidance, MGI (Military Geographic Information), etc.

Perhaps the single major obstacle to operational use of radar image simulation is in the area of data base construction, namely the feature extraction problem. No matter what the nature of the source material, the present approaches, manual (an almost prohibitive restriction in an operational sense) or automatic (computerized pattern recognition), are not suitable. We suggest that an interactive feature extraction approach be one of the principle long range goals.

Many other problem areas were exposed during past efforts of many researchers which must be addressed, ranging from sensitivity analyses through data base compression techniques through alternate methods of simulating cultural targets. These are discussed either in the framework of the long term goals in the subsection or in 7.2, the immediate goals.

7.1.1 Operational Implementation for Image Simulation

An obvious long range goal is to achieve the necessary transfer of technology to utilize radar image simulation in an operational system for a specific mission. To this end the implementation must be cost effective, systems specific, and compatible with all mission requirements. To this end we recommend that the general concepts of state of the art image simulation incorporating results of related studies discussed below be developed for several specific applications. Doing this will document the value of radar image simulation and will increase the demand for solution of the problems presented in this section. In this way, the use of radar image simulation can be accelerated and exploited to the fullest extent possible.

7.1.2 Interactive Feature Extraction

As indicated above, the chief problem apparent at almost every stage of radar image simulation is in feature extraction - identifying the geometry and category (i.e., electromagnetic reflectance) properties of the scene and transferring them to the data base. Classical techniques for feature extraction are manual techniques. Typically, a photo interpreter scans the intelligence data and draws upon his interpretation experience to decide what information to transfer manually to the data base under construction. These decisions are made with as few digital computer image enhancement techniques as possible. This reticence to use available enhancement routines is caused, in part, by the very nature of the automatic routines. They are not generally applicable to any but specific, well-structured, test cases. In addition, use of these techniques requires that the interpreter also be a computer expert. Moreover, the interpreter loses control and visibility of what he is trying to accomplish when he enters the computer world of automatic land-use classification, or pattern recognition, or region definition, or ad infinitum. These reasons have serious ramifications for feature extraction and, consequently, data base construction; they cost money. They cost money in the sense that it takes a much longer time to extract the features for a data base than might otherwise be necessary; data are manipulated by hand and the best information may not be obtained.

Clearly, a tremendous improvement of the product developed, resources expended, and time required could be obtained if a workable marriage between computer and interpreter could be arranged. The computer is very good at manipulating vast amounts of data in short periods of time; the human is not. The human is beyond comparison when it comes to drawing upon learning experience to make decisions. The computer excels at clearly defined repetitive tasks, at statistical analyses, at image enhancements. A cooperative approach in which the human is used to make decisions and guide the processing direction of the software, and the computer is used to manipulate the data rapidly and easily and to remove the drudge from the human would be optimal - optimal in the

sense of maximizing the return for resources expended and minimizing the time and effort. This cooperative approach is called interactive feature extraction, or automated feature extraction (not automatic feature extraction since this is impossible with the state of the art available today).

The concept of interactive feature extraction uses the human for his specific strengths and the computer for its specific strengths. In interactive feature extraction, the computer is used to display, enhance, manipulate, and otherwise aid the human interpreter as he performs his function. Viewed another way, the human is used to make decisions and to guide the computer in real-time as the programs run. Interaction can be accomplished by giving the interpreter a few basic tools with which to communicate his decisions to the computer; a keyboard for commands and joystick for direct specification are probably the minimum to be provided. Given these capabilities, the data base can be built directly as the feature information is processed and decisions are made. Boundaries separating different regions can be specified directly by the interpreter and, while the human is analyzing the next problem area, the computer can build the symbolic data base immediately and display the results. Depending upon the level of sophistication of the interactive software, and the computer and display complex, tremendous savings of resources and improvements in efficiency and quality of the finished product are visualized. Given an interactive feature extraction system, special emphasis could be built in to maximize the use of the intelligence data normally available from which to define the geometry, dielectric properties, and elevation data which are required by radar image simulation.

7.1.3 Microwave Reflectivity Catalog

The key component in transforming the data base into a radar image has been seen to be the parameter σ^0 , i.e. the differential backscattering coefficient for a given homogeneous target. In the best of all possible worlds, an exhaustive measurement program utilizing an airborne multifrequency, multi-polarization, calibrated radar (scatterometer) could be built, flown, and σ^0 versus θ for all potential category targets

(in all states, i.e., moisture conditions, etc.) could be recorded. That is about as realistic as building a data base (that works) for the world by strictly manual techniques; in other words it is an impossible task.

A sound program, however, can be envisioned consisting of a comprehensive literature search resulting in a library catalog of pertinent data, a limited data gathering effort, and, most importantly, development and compilation of relevant scattering theory for use in extrapolating the empirical data available and the library data to the system specifications needed in a given application. At the present time, a very small library of scattering data has been compiled at RSL. Searching the literature so far has shown that significant differences in absolute values of data exist. Only a limited number of different polarizations and frequency data are available. The library must be greatly expanded.

In addition to increasing the sheer amount of library data, they must be verified. This can, at the present time, be most easily done using simulation of a known area where high quality imagery exists. For example, it is not very likely that σ^0 data exists for garden plots (or is it likely that it will ever be obtained). However, on high resolution systems, extensive garden plots could significantly alter the image and should be accounted for. Intuition suggests that the vegetation would have a high moisture content and that in turn suggests using certain agricultural data. The exact choice can be verified for a given frequency, polarization combination, and theory can be used to extend the results to other combinations.

It is almost impossible to obtain the necessary calibrated data from radar imagery. The angular range is insufficient, the ground truth necessary is nonexistent, at least to the degree required, and there are many imponderables about the precise behavior of the imaging system at the time of data collection. But this source may have to be tapped to fill the categories sensed only in images. The present source of σ^0 data originates from calibrated ground based systems or airborne scatterometers.

The ground based system here at RSL (a NASA (National Aeronautics and Space Administration) system) mentioned earlier in this report is

dedicated to civilian remote sensing and accordingly most target signatures are inappropriate for defense programs. Moreover, a ground based system simply does not have the mobility to examine the wide class of targets that need to be investigated. Existing airborne systems are either single frequency and or polarization limited and would not really be appropriate. In summary, a wideband multipolarized airborne calibrated system would be desirable. This system could most likely be built up by subsystems already in the Defense Department inventory and flown on a suitable aircraft. The data gathered in this program would go far toward supporting the simulation efforts in guidance for RPV's (Remotely-Piloted Vehicles). With increased knowledge of the target/sensor interaction, there should be at least an order of magnitude increase in the application of imaging radar systems, themselves, as well as aiding the development of new guidance techniques.

7.1.4 Advanced Modeling: Distributed Targets

The point scattering method, as mentioned earlier, is the ideal method to treat distributed targets for medium to coarse resolution imaging systems. Cultural features would seem to be best treated by an alternate method described later.

Fine resolution systems present a different problem. A key ingredient of the PSM is the assumption that the radar resolution cell can be described by the statistical mean value parameter, σ^0 , the differential scattering cross-section. This assumption, in turn, means that in a given resolution cell, there will be a relatively large number of scattering centers. The number depends on the target type. When the cell becomes small, this assumption can be seen to be in question. Another potential problem is that the cells, themselves, are assumed to be independent. Again, for small cells, this will be invalid. It is not hard to imagine, for example, that the roughness of one cell is correlated with another. These and similar problems arising out of the small cells associated with fine resolution systems merit attention and solution.

The assumption of resolution cell independence also manifests itself in another area that requires study; to wit, the antenna problem. In both real and synthetic aperture, the actual antenna pattern vitally

affects the quality of the final image in a more or less dramatic manner. The assumption that the antenna pattern is constant across a resolution cell has been seen to be valid to a first order approximation. In complex imaging systems, the antenna pattern effect should be included in the model of the processor, especially, pattern degradations due to radome pointing errors, etc. Modeling must be improved in this area.

Closely allied to this problem is that of more accurately modeling the receiver of a real system. Such effects as non linearities, AGC (Automatic Gain Control) limiting, etc., should be included. SAR (Synthetic Aperture Radar) processors present a set of interesting problems in themselves. In some simulation applications, it is required to actually produce simulated "video"; i.e., the simulated electronic signal that the processor uses to create the image. Models to date lack the precision and generality of the point scattering method. We believe that SAR modeling should receive a high priority.

7.1.5 Advanced Modeling: Cultural Targets

Earlier in this report the area spatial filtering method (ASF) for simulating cultural targets was described. This is a method developed in previous years and is seen to do an excellent job of simulating cultural targets from both physical models and high resolution air photographs. This filtering model needs to be investigated to determine its range of applicability. Techniques need to be devised to combine the area spatial filtering radar simulation technique with the point scattering (digital) method. The resulting hybrid radar image simulation model would combine the optical simulation for cultural objects with the digital simulation for distributed objects. Great potential savings in time and resources are offered by this hybrid model. In addition, other techniques need to be investigated. Development of a number of techniques for simulation of a particular class of objects would simplify the simulation process and reduce costs.

Up to the present time the ASF has been implemented on an optical computer. Additional degrees of freedom and more flexibility are foreseen if the optical simulation technique (area spatial filtering method) is implemented on the digital computer. It seems reasonable to anticipate

that models can be constructed which will allow this simulation technique to be used with optical photographs for more than just specular targets. These models are envisioned as containing the necessary information to convert the optical reflectivity densities in the photograph into the appropriate microwave reflectivity densities. Then, this simulation technique (the area spatial filtering technique) when implemented on the digital computer would become a viable alternative to the point scattering simulation method. Some distinct advantages would accrue if this were feasible. First, high resolution photographs would become basic data bases which automatically contain the geometric relationships of the various objects. Second, the cultural features, with their proper orientations, are automatically located in the data bases constructed from such photographs. In addition, interactive (automated) feature extraction techniques could be employed directly with this simulation model to improve the overall efficiency.

At the very least, digital filtering techniques would provide control over the features which are retained in the finished product. Unlike the optical implementation which blindly filters everything in the photograph the digital filtering approach could be made selective. Then, only cultural objects would be simulated and we would not be faced with the problem of extracting the "true" signal from the "false" signal plus noise as we are now, using optics.

7.1.6 Temporal (Seasonal) Changes

As described in the various sections, the parameter, σ^0 , the differential scattering coefficient, is the important parameter representing the electromagnetic target/sensor interaction. It is strongly influenced by moisture content and roughness of the target. In fact, the moisture content is sometimes more important than the intrinsic nature of the target. This has been widely known for some time yet its effect on simulated imagery has generally been ignored and for certain models can't be included. In fact, temporal changes observed in radar imagery constitute the motivation for using radar as a monitoring reconnaissance sensor, i.e., a surveillance instrument. Turned end for end, the question can be raised, what combination of frequency and polarization would give the least noticeable change? It is clear therefore, that temporal (short term) and seasonal (long term) changes in the state of the target must be investigated.

The seasonal and temporal changes severely affect not only the final graytone in the image but boundaries as well. What are thought to be homogeneous regions will, in fact, appear as several divided sub-regions with well defined boundaries separating the different target states. There are many seasonal effects in the terrestrial envelope; these range from rainfall and flooding to snow and ice, from bare ground to young immature crops to old mature crops to harvested crops, from dry soil to wet soil, from bare trees to leaved trees, from frozen ground to thawed ground and etc. Data exists that suggests that the back-scatter coefficient is up to 10 dB higher (most of the dynamic range available in some systems) for spring than for fall deciduous trees (probably true for coniferous to some extent). These data suggest that boundaries between deciduous trees and conifer trees, or meadows, or agriculture, will fluctuate according to the season. Ice is another dramatic case. Water bodies always appear black (specular reflection) with well defined boundaries yet ice appears more like a normal diffuse scatterer. It is easy to imagine the changes in both shore line and total discerned water area changing as ice forms.

A reasonable first phase would be to produce simulations using known data and obtain both qualitative and quantitative measures of the magnitude of the effects. This would certainly be the most economical way to size the problem since large scale flight programs are expensive and are at the mercy of finding the right conditions when the aircraft and system are ready. The temporal and seasonal effects that should be studied range from rainfall (and waterbody size) through vegetation and soil moisture variability to snow studies. As related studies described in this section progress, the seasonal and temporal effects study could similarly advance. That is, the temporal and seasonal effects should be factored in to all the future activities.

7.1.7 Terminal Studies and Future Guidance Systems

In Section 4, the results of validating a specialized version of a PPI imaging radar were presented. The particular system is intended to provide guidance for a remotely piloted vehicle and, hence, image simulation is used to manufacture the reference scenes used for comparison by the navigation systems. The consistency of the results suggests

very strongly that the point scattering method of image simulation can be used to study many unknown parameters in the overall system and thereby achieve increased performance in guidance. For example, many of the assumptions made and the differing success of the reference scene variants clearly indicate, the system has much more sensitivity than previously thought. We believe that this is an area of study that is urgently needed.

The image simulation methodology should not however, be thought of as only providing the reference scenes or systems analysis. Alternate methods of remote guidance can now be proposed, investigated and reliably tested, via simulation, prior to being committed to a hardware program. The two principle methods of navigation using active or passive sensors, profile matching and area correlation, are not necessarily the optimum for a given application. Alternate schemes (e.g., offset aiming) should be examined and bench tested using simulation.

Returning for the moment to the terminal guidance system we suggest that a possible approach to initiating the performance studies would be to systematically degrade in a pairwise fashion the range and angular resolution, thus defining the system sensitivity and establishing an important scene specification. Similarly, the spatial resolution and category content of the raw data base should be similarly varied to establish what must be in the data base itself and, by inference, how it can be made. Many other activities suggest themselves along these same lines, but this brief description is indicative of the nature of the study.

In the same vein (i.e., evaluating system performance and developing specifications), new subsystems should be subjected to rigorous testing via simulation. Since the point scattering method simulates imagery most closely resembling real data, it can be used as the test input data. For example, there are several alternate methods for correlating stored reference scenes with live data. Computer realizations of these methods could be tested prior to hardware implementation. Hardware implementations should be bench tested prior to flight programs. This is not to say that this has not been done in the past,

but using the PSM we can include real scene variability, providing the most realistic analysis and synthesis to date.

7.1.8 Image Quality Measurements for General Application

The quality of a simulated radar image or, for that matter, a real radar image, to suit its intended purpose must presently be assessed by a human being. This determination of quality is very subjective and relies on the judgments of different people who have different bases of experience from which to judge. As the number of applications increases for both simulated and real radar images so also increases the necessity to use more objective image quality measurements. Presumably, these objective image quality measurements would use a digital computer to relate the data of the visual record (recorded in the image) to application. Certain statistical properties of the image should be used to predict the usefulness of an image to satisfy specific objectives. Such a set of measurement criteria do not presently exist. It is recommended that an investigation be conducted to define such a set of image quality measurement parameters.

This set of image quality criteria would be invaluable to the recommended sensitivity study (below). In fact, a limited study of the type recommended here will be required for success in the sensitivity study. Moreover, as use of radar image simulation increases, necessity will decree that these criteria be identified, application by application. The opportunity exists to consolidate these individual efforts and to define the criteria in advance of specific need. Success here will make it easy to relate the value of radar image simulation to each new application and will allow different agencies, or labs, or people, to understand how a particular image may satisfy their needs.

7.1.9 Sensitivity Analysis

The utility and versatility of radar image simulation can be improved and the cost reduced if the minimum level of detail required to be in the data base for specific applications of radar image simulation can be determined. As previously noted, the most expensive part of the radar simulation process is the building of the digital data base. If it can be determined that, for a specific application, the level of

detail in the data base can be reduced, this translates directly into savings of time and money. It is recommended that such an analysis be conducted for the applications of radar image simulation most often used.

7.1.10 Data Compression Techniques

Vast amounts of data must be processed for all but trivial applications of radar image simulation. As presently structured, data bases consist of a point in a matrix, at least, for each pixel (picture element) in the final simulated radar image. This means that most data bases for operational systems are exceptionally large and even the most trivial image handling is inordinately complex. Simple things such as rotations of data bases to alter the look direction (flight line) are tremendously time consuming and expensive. It is recommended that both techniques for data compression and alternate methods for information storage and retrieval be investigated. Investigation of data compression techniques which might be viable for data bases for radar image simulations should be coupled with sensitivity analyses.

Alternate methods for information storage and retrieval probably will require the assembly of a special purpose computer and memory device designed strictly for image processing applications. The great potential value of radar image simulation as a useful tool seems to argue that this investigation needs to be conducted.

7.1.11 Theoretical Models

The increasing applications for radar image simulation require ever larger catalogues of backscatter data. All radar image simulations must use some model for the reflectivity properties (backscatter) of the objects in the scene. These data are required by the simulation model to produce the greyscale data in the simulated image. It is not reasonable to expect to measure and record the backscatter data for all possible permutations and combinations of the variables: Frequency, polarization, categories, seasonal changes, and etc. Theoretical models must be developed to extend and extrapolate the measured data to cases which have not been measured. This is a real need, not a whimsical musing. These theoretical models will form an integral part of radar image simulation as applied to the various applications.

A specific case illustrates this point very well. Circular polarization is desirable from several points of view. Yet virtually no circular polarization data on target/sensor interaction exists, thereby making prediction (simulation) a much riskier venture than need be. Moreover, even in a most ambitious measurements program these data would not be available for some time. Therefore, a study should be undertaken as to how to combine the like and cross-polarized σ^0 data to model circularly polarized data and the results compared with the very limited circular data available.

Thus, the recommendations for certain theoretical studies is seen to be a suggestion for small specific studies aimed at providing solutions to achieve operational status of a given application of simulation rather than an all encompassing unified theory of scattering.

7.1.12 Real and Near Real Time Simulation Updating

Both implicit and explicit in many of the previous recommendations was the phenomenon of target sensitivity to current climatic or environmental state. That is, water bodies could change their shape significantly. The microwave reflectance (i.e., backscattering, could change significantly with changing moisture. Flooding could produce dramatic changes in the scene, etc. All of these could dramatically alter the real radar image as flown and potentially could prevent reliable navigation and guidance from simulated imagery, or real imagery collected under different conditions. The degree to which this might happen is subject to the particular imaging system employed. Many of these questions would be answered in the seasonal/temporal study recommended earlier in this section. However, it is now apparent that there is definitely a temporal problem, only the degree is uncertain.

Of equal importance, is the problem associated with changes in cultural targets. Buildings may be constructed or razed. Large numbers of vehicles may be moved. A number of scenarios can be hypothesized which would lead to dramatic changes in the radar image.

Alternatively we can look at these problems as changes in the data base between the time the original reference scene was constructed and the time of flight. The question then becomes how to structure the simulation so as to permit updating the reference scene to reflect

current conditions in an operational mode, and, of course, in a cost effective manner. The potential solutions range from structuring the original data base in a way that would permit easy geometrical as well as categorical changes and re-simulation, to a way in which modifications could be made to a previous simulation. We recommend that this problem receive careful consideration.

7.1.13 Further Development of Radar Image Simulation Applications

The general concept of radar image simulation has been developed. What remains is to extend the general concept to specific applications. With development of each application will come unique, new, problems which must be solved. These problems will run the gamut from feature extraction for building data bases to image handling problems.

It is recommended that the general concept be developed for several specific applications the problems identified and solved and the value determined. Potential applications are: Evaluation of stereo-radar techniques, exploration of interferometry, the effect of random motion, the evaluation of change detection systems, etc. In short, we recommend that applications of radar imaging in the fields of reconnaissance and guidance be evaluated using simulation prior to building hardware based solely on mathematical derivations.

A specific example will make the point quite clear. Many proposals for obtaining stereo radar imagery have been made but only a few have been implemented. A larger number of computational algorithms have been suggested for calculating height from stereo radar. Using the point scattering image simulation method, both the proposed system and computational algorithms could be readily examined and quantitatively evaluated.

7.1.14 Other Sensor Systems

As it is believed that the trend in intelligence gathering systems is to use electro-optical systems which are an aggregate of a number of different sensors, it is recommended that the concept of simulation be extended to these other sensors. Radar is just one sensor of this aggregate. Another sensor, for example, which seems to have great potential value is the FLIR (Forward-Looking Infra-Red). Other sensors

also exist. These sensors need to be modeled and the underlying phenomena investigated. It would appear that transfer functions analogous to the famous radar equation relating the various aspects of sensor, scene, and medium can be obtained. Since applications for these sensors are expected to increase, it is recommended that these investigations be conducted.

7.2 Short Term Goals

In the past year we have had the opportunity to evaluate the problems, requirements, and obstacles of radar image simulation. As we believe our radar simulation model has opened the door for present and future applications of radar image simulation, it is increasingly important to start the work to solve these problems, satisfy the requirements, and overcome the obstacles. A succinct listing of the more important (as we order them) items requiring immediate attention follows. This listing is ordered into four basic categories: (1) Future Terminal Guidance Studies; (2) Data Base Construction; (3) Simulation Problems; (4) Related (future) Applications.

7.2.1 Terminal Guidance Studies

For the moment, let us consider guidance in general terms. In this new era of military defense in which we are changing our "counterforce" strategy* from the bomber, accurate delivery of missile projectiles is increasingly important. The task of delivering an explosive projectile accurately enough to destroy an intended target becomes crucial. This task has three basic components: (1) Distinguish the target from its surroundings; (2) Determine the exact position of the target relative to the launching point of the missile; (3) Guide the projectile onto the target. It is this question of guidance which is of interest here.

*"Counterforce" strategy is defined by Tsipis²⁸ as a nuclear-war strategy that relies at least in part on the ability to destroy the land-based offensive missiles of the U.S.S.R. in their reinforced-concrete silos.

²⁸Tsipis, K., "The Accuracy of Strategic Missiles," Scientific American, volume 233, no. 1, July 1975.

The lethality of a warhead directed against a hardened site rises much more rapidly with improvements in accuracy than it does with increases in warhead yield. Hence, it is the accuracy of delivery of the projectile that is crucial rather than its size²⁸. The problem of the accuracy of delivery of the projectile exists no matter whether the missile is designed for tactical or strategic missions. In fact, the tactical guidance problem is more difficult because the target area cannot usually be completely specified far in advance of need. The targets are typically mobile whereas strategic targets such as concrete missile silos, weapons factories, etc., are immobile. This difference is a significant one. It means there will be less time to obtain and use guidance parameters in the tactical situation. But, this is not to minimize the strategic guidance problem. Guidance errors accumulate with time. The farther away a target is, the more crucial it is to be able to program accurately the guidance parameters.

Two basic alternative approaches to this problem are presently being developed for both strategic and tactical situations: Ballistic and cruise missiles. A ballistic missile is guided for the first few minutes of its flight as well as, perhaps, for the terminal phase whereas a cruise missile, since it flies at subsonic speeds and at low altitudes, requires periodic guidance throughout its flight. In both approaches, ballistic and cruise, for both tactical and strategic situations, radar image simulation offers an advanced tool to improve the guidance problem and, hence, the lethality of the projectile. It offers both terminal guidance for ballistic as well as periodic guidance for cruise missiles. In the sections that follow, we will discuss the application of radar image simulation technology and related studies to the problem of terminal guidance for a tactical ballistic missile. This emphasis on terminal guidance for the tactical ballistic missile is a natural focus of work we just completed and reported in this document (Section 4.) and is not a reflection of limitations of either our radar

²⁸ Tsipis, K., "The Accuracy of Strategic Missiles," Scientific American, vol. 233, no. 1, July, 1975.

image simulation model or applications of the model. The technology is compatible with all guidance problems and applications. This should be kept in mind when evaluating the various recommended studies that follow.

These are not the only guidance problems radar image simulation can serve. Another very important problem is navigation briefing and training for fighter/bomber sorties. We understand that present radar "simulator" equipment uses optical photographic techniques to mimic the radar return from the terrain over which the fighter/bomber is to be flown. We further understand from private conversations with fighter pilots that the simulator products are not used for most missions. Certainly, research is being conducted into ways to improve the situation. For instance, a possible long-term solution may exist in completion of the DRLMS (Digital Radar Land-Mass Simulator) work of DMA (Defense Mapping Agency). Also, several military agencies and commercial companies are known to be working on the problem. Regardless, we believe that ultimate solution of the problem rests with accurate application of radar image simulation techniques and, further, we believe we can make a contribution to the solution of the problem.

These are the most obvious guidance applications for the use of radar image simulation which come to mind. In the following sections several studies are recommended to be carried out which seem to us to be the next logical step in the development and application of radar image simulation to the problem of guidance. While the foregoing discussion has been very general and purposely was not limited to the mission objectives of the Army, the studies described below are specifically tailored to the mission objectives of the Army. It is easy to extrapolate them to the mission objectives of the other services.

7.2.1.1 Seasonal Variations

Initial work and results are reported in this document of a study we performed on a terminal guidance system which uses the Correlatron⁷ (Section 4.). As previously noted, this study was conducted for one target site, one radar system, and one set of flight parameters. It was also noted that this did not represent exhaustive testing, but, for other reasons, the reference scene generation techniques developed here were believed to be superlative. Now the techniques should be employed to evaluate the concept of terminal guidance using the Correlatron and other devices, both analog and digital.

Many aspects of this guidance concept (i.e., area correlation, in general) have been unresolved. One of the most important of these is the question of whether or not the guidance system consisting of both the radar and correlation device is sensitive to either seasonal or meteorological conditions. We are unaware of any exhaustive study into the sensitivity of cross correlation between an image made by a particular radar system and a simulated radar image for such conditions. However, it can be shown that changes of the season and meteorological condition can have a dramatic effect on the radar return²⁹ and on the image³⁰ of a particular radar. The sensitivity of the Correlatron guidance system to such changes needs to be established. The answer has important ramifications for the reference generation technology and supporting equipment and data requirements. At one extreme, a single set of reference scenes will suffice to produce an acceptable CEP (Critical Error Probability) for all seasonal and weather changes.

⁷ Klass, Philip J., "Guidance Device Set for Pershing Tests," Aviation Week and Space Technology, May 12, 1975.

²⁹ Bush, T., F. T. Ulaby, T. Metzler and H. Stiles, "Seasonal Variation of the Microwave Scattering Properties of the Deciduous Trees as Measured in the 1-18GHz Spectral Range," TR 177-60, Remote Sensing Laboratory, The University of Kansas, June, 1976.

³⁰ "Military Thematic Mapping and Map Compilation from Radar Imagery (u)", vol. I and II, Goodyear Aerospace, Report AL-36178A, November, 1972 (Classified/Confidential).

At the other extreme, a new set of reference scenes will be required for every change greater than some minimum. Exactly what the Correlatron requires needs to be established. (Note: Seasonal and meteorological effects on radar are a fact of life which must be investigated no matter what radar guidance technique is proposed and are not limited to consideration only for the Correlatron system.)

To date, only two sets of flight data have been collected for the target site for which we produced reference scenes. The first set of flight data were collected in October, 1975; the second in June, 1977. As might be expected since this is a test program, changes were made in the PPI (Plan-Position Indicator) hardware between those data collection periods. Unfortunately, this prevents direct comparison between those data sets. There were no major meteorological differences between those two periods; they both represented an average moisture situation typical of extended high-pressure systems in the area. No significant rain fell during either period. The only significant difference identified between the two periods is the vegetation growth season. But ground truth adequate to determine the soil moisture and maturity of the vegetation was apparently not collected. It is known that during both periods the deciduous trees present in the target site were fully leaved. They were beginning to enter their fall color stage during the October data collection period, but it is unknown what percentage of the area had begun to go dormant. Deciduous forests represent a considerable percentage of the area present in the target site (Pickwick Landing Dam). It should be noted that Ulably has reported a very significant difference in the return from spring and fall deciduous trees²⁹. If the maturity conditions of the fall forests were known, this might provide important information concerning the question of seasonal impact on the correlation guidance system. In the absence of these data, it is assumed that all the flight data collected to date represent only a single seasonal and meteorological condition. Thus, it is reasonable to hypothesize that neither the guidance technique, nor the

²⁹ Bush, T., F. T. Ulably, T. Metzler and H. Stiles, "Seasonal Variation of the Microwave Scattering Properties of the Deciduous Trees as Measured in the 1-18 GHz Spectral Range," TR 177-60, Remote Sensing Laboratory, The University of Kansas, June, 1976.

reference scene generation technique have been tested in an operational mode to measure sensitivity to seasonal and meteorological change.

We understand that such a test is presently proposed to be conducted for a test site in the vicinity of Watertown, New York, during either the winter of 1977/78 and summer of 1978, or the summer of 1978 and the winter of 1978/79. Our radar image simulation model represents an ideal tool to support this program. Maximum information can be obtained if the work at the Pickwick site is used in the early stages while the Watertown site data base is being constructed. We recommend that a two-part study be implemented in support of the seasonal test to be flown at Watertown. A possible framework for this study might be:

A. Pickwick Site.

Construct a hypothetical winter data base from the existing one. Produce "winter" reference scenes (simulated radar images) from this hypothetical winter data base. Test the "winter" reference scenes on the Correlation against the October and June flight data. Evaluate the results. Positive correlation results (acceptable correlation within a specified CEP) would convey important information: The sensitivity of the Correlation guidance system to seasonal changes is less than feared. Negative results (poor correlation) reinforce the need for the flight test program.

B. Watertown Site.

Construct, at least, both a summer and a winter data base representing the "average" season for the target site(s). Produce reference scenes from the data bases. Test each reference scene against both the same season and other season flight data. Evaluate the results. Devise other test conditions as appropriate.

7.2.1.2 Alternate Approach to Model Ground Return

As previously noted, empirical backscatter data (σ^0) have been used in all the work presented in this document. A study needs to be initiated to search for an alternative to empirical σ^0 to model the radar return from the ground. The results of this study can have far-reaching consequences for the viability of the correlation guidance concept. In particular, if it is found that a combination of empirical σ^0 data with a simple theoretical

model such as Clapp's³¹ is adequate for a large percentage of features in the terrestrial envelope, the implications are enormous.

At present, a severe weakness in the correlation guidance concept is the potential requirement to measure and record the backscatter response (at a particular frequency and polarization) versus angle of incidence for a very large number of categories over a wide range of seasonal and moisture conditions. The sheer size of this job might overshadow the value of the correlation guidance concept. However, if it were only necessary to know the σ° value for one point on the curve for many categories, the task of obtaining σ° data becomes more tractable.

An investigation should be started to determine if adequate reference scenes can be produced given only a single σ° point for each category and a simple theoretical model to extend and extrapolate that point. The existing Pickwick data base can be used for this work and, as other data bases are constructed, they can be included in the study thereby increasing the number of categories which are tested. The study might be structured to evaluate a number of simple candidate theoretical models. Reference scenes could be formed using the various combinations of empirical σ° data and theoretical models. These reference scenes could then be tested against the flight data on the Correlatron or a digital implementation of the correlation process. Analysis of the results would determine if this approach is feasible. If it is, this concept of guidance would be given renewed viability.

7.2.1.3 Step-Wise Resolution Degradation Study

As a result of the terminal guidance work reported in this document (Section 4.) the question can be raised as to what features in the target reference scene are essential, and to what resolution must these features be known. This question has serious operational ramifications. The less detail required to be included in a reference scene the more desirable in an operational sense becomes the terminal guidance scheme built around the correlation. This enhanced desirability would come from the projected relaxation of requirements placed on the information content of the data bases which must be constructed ultimately for each

³¹ Cosgriff, R. L., W. R. Peake, and R. C. Taylor, "Terrain Scattering Properties for Sensor System Design (Terrain Handbook)," Engineering Experiment Station Bulletin, The Ohio State University, vol. XXIX, no. 3, pp. 10-12.

target site. This means that as requirements are relaxed the data bases can be constructed faster and easier. In an operational environment speed and flexibility might make the difference between success and failure. In fact, it can be hypothesized that a prime consideration of whether or not correlation terminal guidance systems ever become operational would be the ease with which reference scene data bases can be constructed, maintained, and updated.

Our reference scene generation model and computer implementation presents an ideal tool with which to perform these studies. The basic idea behind the studies would be to produce a number of reference scenes representing step-wise degradation in range resolution, or azimuth resolution, of feature information singly or in combinations. Each of the reference scenes would then be correlated against the real PPI video data collected from the same target site. The results would be evaluated and appropriate criteria established for making reference scenes in an operational environment.

These studies could be performed separately as a need arose. For instance, range and azimuth resolution requirements could be determined easily for the existing Pickwick data base. Reference scenes could be made with all parameters held constant except either, or both, range or azimuth resolution which would be step-wise degraded to the point at which the desired CEP was no longer attained when correlated against the flight data. At this point the data base could be changed to represent a new level of feature information and reference scenes having variously degraded range and azimuth resolutions could be made. These would be correlated, results evaluated, and another feature level change in the data base made until the desired (or optimal) results were obtained.

7.2.1.4 Parameter Optimization Study

The Point Scattering radar image simulation model represents an ideal tool for parameter optimization studies. As previously noted, the model is mathematically rigorous and is a faithful reproduction of the complete imaging radar closed system consisting of the radar transmitter/receiver, ground and electromagnetic energy interaction, and image medium.

This means that we have complete control over the input/output requirements, relationships, and products. As this model has been implemented on a high-speed digital computer, it can be changed easily to represent a different operational configuration. Many radar parameters and flight and target conditions can be evaluated readily without the costly necessity to fly, or build and fly hardware missions. Since this is the case, the model and its capabilities should be used to study some of the other unresolved terminal guidance questions to which we previously alluded. The following listing represents some of the more important parameters which might be analyzed.:

A. Polarization/Frequency Combination.

Determine the optimum transmitter frequency and transmit/receive polarization pair to maximize the probability of guidance within the CEP. Presumably this task would start with the premise of what features it was desired to guide on (unambiguously distinguish) and then a test would be structured to identify what frequency/polarization combination would best separate those features while at the same time blurring the distinction between all undesirable changes such as the seasonal changes of agriculture.

B. Antenna Gain Function.

Determine the optimum antenna gain function to enhance the probability of guidance within the required CEP.

C. Resolution Element Size.

Determine the optimum antenna azimuth beamwidth and transmitter pulse length to maximize the probability of detection of the desired guidance features and to minimize detection of all others.

D. Antenna Scan Format.

Determine the optimum antenna scan format.

E. Receiver Detection Scheme.

Determine the optimum receiver detection scheme to maximize the probability of detection of the desired guidance features.

F. AGC Design.

Determine the optimum AGC (Automatic Gain Control) design to maximize detection of desired features.

G. Guidance Device.

Evaluate the correlation systems and determine how improvements might be made to maximize operation for the desired guidance features.

All of these studies, and more, could and should be performed since a tool such as radar image simulation is available. There are several ways in which these studies might be performed. First, they might be conducted using the existing software implementations of the radar image simulation model and the Correlatron. Alternatively, our radar image simulation model might be implemented on ETL's (Engineer Topographic Laboratories) DIAL* computer complex thereby taking advantage of both the parallel processing power available and the digital implementation of a model of the Correlatron. The second alternative is the most powerful one. The first alternative is much slower to produce results due to the vast differences in computer capabilities, but it is immediately available. No matter what approach is taken, one of these or a different one, if guidance by area correlation is to be successful these studies must be performed.

7.2.1.5 Evaluate Guidance Concepts

Radar image simulation offers a promising approach to the problem of "pilotless" location and guidance of both missiles (ballistic and cruise) and aircraft. Radar image simulation offers a powerful tool for this problem because it is highly desirable to use imaging radars for guidance (at least in conjunction with other sensors) because of the essentially all-weather operational capabilities and the potential for high accuracy provided by radar. At this point in guidance development, no single approach has been shown to be clearly superior to all others. Many approaches are being investigated. In most concepts, terrain data are stored in "on-board" memory (film, digital, or other) and location is estimated through a correlation or a map-matching (terrain-matching)

* DIAL is an acronym standing for Digital Image Analysis Laboratory. This laboratory is an exceptionally powerful computational facility consisting of a Goodyear STARAN, CDC 6400, PDP 1145's, and other, supporting equipment and software.

process. A study needs to be conducted to identify reasonable guidance techniques and evaluate their merits relative to the task of guidance and to the possibility of being able to construct operational systems.

Radar image simulation has been shown in the terminal guidance work reported in this document to be capable of producing reference scenes for correlation with flight radar imagery (using the Correlatron) in which very accurate guidance is accomplished. This is not to suggest, however, that the guidance concept using the Correlatron is optimal. Far from it for much work is yet to be done as the earlier suggested studies indicate, before this guidance concept is touted as the optimal choice. Nevertheless, it has been clearly shown that radar imagery and radar image simulation together can provide a powerful guidance team. The work should now be started to discover how best to make effective use of these capabilities in the guidance scenario.

Among the candidate guidance techniques which might use radar imagery and radar image simulation and thus should be evaluated are area correlation such as embodied in the Correlatron⁷, profile-matching as in the Tercom³², map-matching using a range-scan radar³³, pattern recognition based upon target image tracking³⁴, and other, more exotic techniques. The study to be conducted should evaluate each technique relative to the task of guidance, to supporting intelligence and equipment requirements, to seasonal effects, and to cost-effective implementation. Since this is a large task, it should be conducted in stages. The

⁷ Klass, Philip J., "Guidance Device Set for Pershing Tests," Aviation Week and Space Technology, May 12, 1975.

³² Tsipis, Kosta, "Cruise Missiles," Scientific American, vol. 236, no. 2, February, 1977.

³³ James, L. T., "Map-Matching Estimation of Location Using Range Scan Radar Images," IEEE National Aerospace and Electronics Conference, NAECON '74, May, 1974.

³⁴ Moskowitz, S., "Terminal Guidance by Pattern Recognition - A New Approach," IEEE Trans. Aerospace and Navigational Electronics, pp. 254-265, December, 1964.

first stage would probably consist of evaluating area correlation, the Correlatron, and analogues of the concept. For instance, the Correlatron, which is an analog device, and a digital, "computerized" version of the Correlatron might be separately evaluated and then compared. At the same time other electro-optical approaches might be considered and the optimal choice which best satisfies the criteria might be selected. Subsequent stages would depend, for the most part, on the findings of the first stage as well as the guidance needs which are, or are not satisfied by those findings.

7.2.1.6 Field Reference Scene Update

At some point in the future, area Correlation concept of guidance may be deployed in an operational situation. To support that potential operational use of this guidance concept, work needs to be initiated to develop the technology for updating in the field on very short notice the data bases and reference scenes of various target sites. The point stressed here is the need to develop technology which can be employed by military personnel while maintaining pre-conceived standards for speed and accuracy.

Some of the other studies suggested here are vital to development of the technology. In particular, studies concerning the impacts of seasonal changes on reference scene requirements, level of feature information, range and azimuth resolution, and ground return model are vital.

A study should be initiated to determine what intelligence data requirements and equipment will be necessary for field updates of reference scenes. The same technology would be required to support mobile field units in the tactical mission. Upon conclusion of this, and the other studies, specifications could be written which set-out the requirements for mobile field units.

It is very important for this study to be conducted in parallel with the other studies because of the potential for feed-back. It is easy to imagine that hardware limitations will be encountered because of the requirement of portability for field use. These limitations can be factored into the other studies and appropriate adjustments made to evaluate requirements for realizable equipment. Interaction between

these studies, if properly coordinated, can have far-reaching consequences. The results might dictate success where any other approach invites failure.

7.2.1.7 Reference Scene Technology Evaluation

As indicated (Section 4.), our approach and reference scene generation model was successful. Why?

The only answer available today is we were successful because we rigorously modeled, at least, the first-order (most important) effects of the problem. That answer is unsatisfactory because it is not definitive. A study needs to be undertaken to determine why we were so successful. This question has important natural consequences for the potential operational deployment of the Correlatron guidance system.

In particular, the source intelligence data, the data base construction and information content, the ground return model, the Correlatron system all need to be investigated, the requirements and interrelationships established, and the sensitivity of the system to various perturbations defined. Results of this study will go a long way toward defining what features the system guides on and what information level needs to be included in the data base.

7.2.1.8 Development of the Area Spatial Filtering Technique for PPI

The feasibility of the area spatial filtering techniques for radar image simulation of cultural targets has been established⁶. Previously, a fixed look-direction (corresponding to a side-looking radar) was implemented optically by selective filtering with a stationary mask in the frequency plane of the coherent processor. More recently a method has been proposed to reproduce the effects of mechanical rotation or electronically phased array scanning of a PPI system antenna. The resultant radar simulations should properly treat cultural targets of a scene as though they were being imaged by an approaching (oblique or orthogonal) PPI radar. However, a theoretical basis for the PPI simulation concept using the ASF approach has not been established, nor have results been produced for validation. Just as the area spatial filtering method for SLAR cultural feature simulation has been shown to be a viable alternative

⁶ Frost, V. S., J. L. Abbott, V. H. Kaupp, and J. C. Holtzman, "A Mathematical Model for Terrain-Imaging Radar and Its Potential Application to Radar Image Simulation," TR 319-6, Remote Sensing Laboratory, The University of Kansas, November, 1976.

to digital simulation because of significant savings in data base construction, the ASF (Area Spatial Filtering) PPI simulation has related advantages. Using aerial photography or other image data as the microwave reflectivity map for cultural targets of a scene results in an attractive savings in data base construction and simulation computer time.

1. , if water boundaries and cultural targets are sufficient for correlation, an implementation of the area spatial filtering approach for a PPI radar image simulation might ultimately lead to the production of reference scenes in real time.

7.2.2 Data Base Studies

The ground truth data base is a major input requirement of the point scattering radar image simulation computer programs. Since the radar simulation model has been implemented on a digital computer, the data base must be in digital format. The data base can be considered to be a digital model of the physical (geometric) and radar return (dielectric) properties of the ground. It is a digital representation of the different features and elevation variations of the terrain present in the target scene. Typically, this data base consists of a digital matrix containing four dimensions. These four dimensions are the range and azimuth coordinates, elevation, and radar backscatter category of each point on the ground. It is this matrix upon which the simulation program operates to calculate such parameters as look-direction, range, angle-of-incidence, shadow, layover, range compression, local slope of the terrain, local angle-of-incidence, etc. In other words, the ground truth data base is a crucial part of the point scattering radar image simulation model.

Construction of the ground truth data base is a very large problem facing radar simulation. This is especially so because of the way that data bases are constructed. They are, typically, built using manual techniques. Once the source intelligence (photos, maps, etc.) have been obtained for a particular site, a photo-interpreter uses these imagery and his knowledge and intuition to construct a data base map of the area. This data base map is usually drawn by hand. Major features may be traced or transferred from the source imagery. Locations of minor features and subdivisions are usually subjective determinations by the photo-interpreter. The name most often applied to this task is feature extraction. Construction of this hand-drawn data base map is a major effort requiring judgment, accuracy, and knowledge of the area or similar areas.

When this hand-drawn data base map has been finished it represents a symbolic radar category map of the target site. For use on the digital computer, this line drawing must be digitized and constructed into a digital matrix. A large table digitizer is typically used to digitize the boundaries on the category map. A human operator traces each boundary with the cursor of the digitizer and the computer attached to the digitizer table periodically samples and records the position of the cursor. After digitization, the boundary data must be converted into a digital matrix and elevation data must be obtained and added.

Construction of data bases for radar image simulation is a slow, time-consuming process. As is evident, most of the work is performed by humans. The techniques used are generally manual ones. What is needed is a way to improve and speed-up this process. Such a way is offered by interactive feature extraction. Interactive feature extraction is a cooperative approach in which the human is used to make decisions and guide the processing direction of the software, and the computer is used to manipulate the data rapidly and easily and to remove the drudge from the human. Several studies are recommended to be performed in the following sections.

A companion problem to rapid construction of large data bases is data base storage, retrieval, and processing. Studies need to be conducted to solve these problems to facilitate operational deployment of radar image simulation.

7.2.2.1 Interactive Feature Extraction

Preliminary interactive feature extraction studies have been conducted and reported in this document (Section 5.4). Also reported is an initial design concept of an interactive feature extraction system. Since we project that radar image simulation will find more operational military uses as an advanced tool for guidance and discrimination, we suggest that this work be continued.

These increased military applications of radar image simulation will almost certainly require rapid and accurate construction of data bases. Even though the term "interactive" has been over-worked in the past, construction of data bases for radar image simulation is one field

where it fits like a glove. Interactive feature extraction designed specifically for radar simulation draws upon the strengths of both man and machine, and, with proper design, should produce superior results. Our experience with all facets of radar image simulation should improve the probability of the approach suggested here being successful. An attempt has been made to tune a system so that the human can specify directly from the source intelligence imagery to the final digital data base matrix, by-passing all the intermediate manual steps. Much work remains to be done, but given the premise that radar image simulation is a potentially worthwhile operational tool, the interactive feature extraction system is a very necessary part.

7.2.2.2 Rapid Data Base Update

Besides facilitating feature extraction for data base construction, an interactive feature extraction system would prove to be a very useful tool in other areas of radar image simulation. An area in particular that would be enhanced by the introduction of such a system is the periodic updating of existing data bases to reflect changes in the ground scene. Such updates are necessitated by changes in the ground scene due to such factors as seasonal variations (trees, foliage, and crops changing), meteorological changes (presence or absence of snow, rain, etc.), and other events which alter the ground scene sufficiently to affect the radar image. In many applications (especially military applications), the capability to update rapidly radar image data bases will play a vital role. For instance, if the radar image simulation is being used as a reference scene for a terminal guidance device, and several hours before use the navigation scene is covered with eight inches of snow, the data base and reference scene probably must be updated to accurately reflect ground conditions. In such a situation where the radar image simulation is being used to model a dynamic environment, there must exist a fast method to update the data base. Once again, the interactive feature extraction system could be used effectively to solve the problem. Using the system, an operator in a short time could easily examine the data base and alter it to match the situation by merging, expanding, or contracting regions, changing boundaries, and altering the categories or contents of the data base.

We recommend that a study be conducted to determine the special needs of the rapid update problem. These special requirements should then be incorporated in the design and implementation of an interactive feature extraction system. Or, alternatively, a special system could be designed and built to handle just the problem of rapidly updating data bases. This special system would be almost certainly an interactive one.

7.2.2.3 Data Compression Techniques

Most data bases for operational systems are exceptionally large and even the most trivial image handling is inordinately complex. Simple things such as rotations of data bases to alter the look direction (flight line) are tremendously time consuming and expensive. It is recommended that both techniques for data compression and alternate methods for information storage and retrieval be investigated. Since data bases used in radar image simulation have several unique features and since there are several critical limitations on them, techniques of data handling and compression for more general image processing are not necessarily optimal and may not be applicable. On the other hand, procedures rejected for more general image data bases may be well suited when aimed at radar simulation data bases for a specific application.

Alternate methods for information storage and retrieval probably will require the assembly of a special purpose computer and memory device designed strictly for image processing applications. The great potential value of radar image simulation as a useful tool seems to argue that this investigation needs to be conducted.

7.2.2.4 Source Intelligence Analysis

A study needs to be conducted to determine what the minimum source intelligence requirements are to construct a radar image simulation data base capable of satisfying specific mission requirements. It has been conjectured (Section 5.3.3) that the best possible data base could be built using as many different sources of input intelligence data as can be obtained. Some potential sources of input data are optical high-resolution aerial photographs, IR (Infra-Red) imagery, radar imagery, topographic maps, etc. Realistic limits need to be defined for this conjecture. The exact requirements need to be defined as radar systems and applications become operational, speed and accuracy of data base construction become paramount.

This study might be conducted in parallel with a radar data base sensitivity study presently in progress. The two studies complement each other very well; they both seek to define how to maximize the information content of a data base.

7.2.3 Simulation Problems

The concept of radar image simulation has been developed and shown to be a viable tool for a multitude of potential applications. Many areas have been identified as a result of the work reported in this document which require additional study. With significant progress in these areas, radar image simulation can be exploited to the fullest extent possible. Without significant progress, the potential number of operational applications will be severely limited. The following broadly defined areas of research hold the long range key to the future of radar image simulation. The following general areas represent the natural focus of earlier work together with the work performed and reported in this document and extend the concepts.

7.2.3.1 Comprehensive Compilation of Backscatter Data

The concept of radar image simulation has been shown to be a valuable tool for a multitude of potential applications. A major obstacle must be overcome before the promise offered by radar image simulation can be realized. This obstacle is the necessity to have backscatter data available for much of the terrestrial envelope at many microwave frequencies and polarizations. In fact, this same obstacle is a main reason why radar imagery is not used to the fullest extent possible. So little is presently known about the backscatter properties of most objects in the terrestrial envelope that the visual record of a parameter, present in images as the greytone variation (i.e., texture and tone), is not properly utilized for the information it contains. With more certain knowledge of the backscatter properties of objects in a scene would come a significant increase in intelligence gathered from each image. A comprehensive compilation of σ^0 versus θ data should be performed. The result of this effort should include both empirical backscatter data and theoretical models. This study would require an extensive literature search to gather all available empirical data and theoretical backscatter

models. The theoretical models should be evaluated to determine their applicability to the radar image simulation problem and they should be examined to determine techniques to extend and extrapolate available empirical data across frequencies, polarizations, and depression angles.

7.2.3.2 Evaluate "Optical" Simulation Technique

A radar image simulation model called the Area Spatial Filtering (ASF) method has been developed and is presently implemented on an optical computer⁶. An analytical approach to the problem resulted in a unique description of radar image simulation by considering the image product, radar system, and ground scene to be a closed system. The main difficulty with this technique is obtaining a model of the microwave reflectivity density for the objects in the scene to be simulated. If we assume that for specular reflection the reflectivity density is relatively independent of the wavelength, then a photograph of the scene taken at optical wavelengths can be used to model the microwave reflectivity density for cultural targets (specular reflectors). Given this assumption about specular reflection, the ASF model handles cultural targets very well using optical photographs for the reflectivity densities in the scene.

The applicability of this technique to cultural features should be investigated, the validity of such simulations established, and appropriate simulations of the cultural features in the data bases produced of various test sites for comparison or combination with the ordinary digital simulations.

7.2.3.3 Hybrid Radar Simulation Study

Simulating the microwave return from cultural objects (houses, streets, automobiles, airplanes, etc.) by digital computer via the point scattering method is extremely inefficient and expensive because of the tremendous requirements of the simulation model for detailed geometric and dielectric ground truth data. Just the manhours of time alone required to accurately specify these data to the precision required is prohibitive. Depending

⁶ Frost, V. S., J. L. Abbott, V. H. Kaupp, and J. C. Holtzman, "A Mathematical Model for Terrain-Imaging Radar and Its Potential Application to Radar Image Simulation," TR 319-6, Remote Sensing Laboratory, The University of Kansas, November, 1976.

upon the resolution of the radar which is being simulated and the application for which the image is being made, it may be necessary to specify the orientation and geometry of each building (including dihedral corners, elevation, dielectric properties, and etc.). It is clear that the problem can rapidly get out of hand.

A promising alternate simulation technique is offered by the area spatial filtering method⁶. This method appears to be valid for the simulation of cultural objects and is orders of magnitude faster than digital techniques.

The optimum method for simulating a scene consisting of both distributed and cultural targets would combine the strengths of both techniques, digital simulation techniques for distributed targets and optical simulation for cultural targets. This marriage of the two techniques results in a hybrid model for the simulation of radar imagery which is optimal in the sense of maximizing output information while conserving time and resources.

A study should be conducted to evaluate the feasibility of developing this hybrid simulation model. An analysis shall be performed to determine the potential value of further work on this model.

7.2.3.4 Evaluate Digital Filtering Techniques for "Optical" Simulation

The area spatial filtering radar image simulation model⁶ has been implemented on an optical computer. This simulation model appears to be valid for cultural targets (i.e., specular reflectors). If this is true, then high resolution photographs can be used to model the reflectivity densities of the various specular reflectors in a scene. However, a very large proportion of most photographs do not contain specular reflectors. Implementing this simulation technique on the optics bench, therefore, means that all the unwanted features in the scene will receive the same processing and will, thus, become "noise" in the output simulation. An alternative approach for implementation of the technique is sought. A promising candidate is digital filtering techniques³⁵.

⁶ Frost, V. S., J. L. Abbott, V. H. Kaupp, and J. C. Holtzman, "A Mathematical Model for Terrain-Imaging Radar and Its Potential Application to Radar Image Simulation," TR 319-6, Remote Sensing Laboratory, The University of Kansas, November, 1976.

³⁵ Bendat, J. S. and A. G. Piersol, Random Data: Analysis and Measurement Procedures, Wiley-Interscience, 1971.

The benefits to be reaped from such an implementation extend to all facets of radar image simulation work and, especially to the future phases of the terminal guidance work reported here. We recommend that the following operational computer programs be developed and implemented on the DIAL system:

- A. SLAR (Side-Looking Airborne Radar) model;
- B. PPI (Plan-Position Indicator) model;
- C. Terminal guidance reference scene model;
- D. Interactive feature extraction.

7.2.4 Extending the Simulation Frontiers

The point scattering radar image simulation model and its software implementations have been verified in the work reported in this document. The model rigorously treats as a closed system the properties of the radar system being modeled, ground scene, and image medium. It mathematically expresses the relationships and interrelationships between these various aspects of the closed system. Implicit in this model are all the normal radar effects such as layover, shadow, range compression, etc. These and other effects depend entirely upon the software implementation for accurate realization. As the results show, the model, its software implementation, the ground truth data bases and feature extraction techniques, and the use of empirical σ^0 data to model the radar return from the ground, have seen the science of radar image simulation make the transition with this work from an interesting research problem to an engineering tool available for many different applications. The opportunity should not be lost to extend the results obtained here by applying our radar simulation model to solve present and future problems as they occur.

7.2.4.1 Application of Simulation Technology

The radar image simulation technology developed and reported in this document should be applied to some specific radar systems and missions. In addition to solving some operational problems, doing this will document the value of radar image simulation and will increase the demand for solution of the other problems presented here. In this way the advanced tool of radar image simulation will be utilized to solve some specific mission problems and the use of radar image simulation can be accelerated and exploited to the fullest extent possible.

A suggested first mission to which radar simulation might be applied is change detection. A specific radar system should be modeled for this task. Basically, the concept involves the use of radar image simulation to baseline conditions of candidate areas in two different ways.

First, subsequent real flight imagery obtained from the candidate areas would be compared to the baseline imagery and changes noted. The baseline imagery would, of course, be formed from a data base of the area with the simulation parameters set-up to mimic the real system and flight parameters. This would be done so that frequency, polarization, radar transfer function, altitude, heading, look-directions, angles-of-incidence, etc., would be identical between the flight radar images and baseline simulated images. Therefore, to the extent the data base is a faithful reproduction of the target area at the desired frequency, polarization, and resolution, the differences existing between flight and baseline images are the changes sought.

The second approach involves using our radar simulation technology to alter pre-existing actual flight radar imagery of an important area to the conditions existing for a later set of imagery of the same area because it might have been taken by a different system (or the same) from a different altitude, look-direction, etc. In this scheme, actual flight imagery is the baseline for an area. The simulation technology would be used to change the baseline image to match the radar system and flight parameters of the subsequent comparison imagery obtained for the area (or vice versa). A data base would still be used in this approach, but the real image being altered would contain the information which must be preserved and faithfully treated. Since radar system parameters and flight parameters are being matched, and since the information in the original image is being preserved in this approach, the differences existing between the baseline and subsequent imagery are the changes sought.

Note that the technology which would be developed in this second approach has several other potential applications. Basically, this approach involves developing the capability to change a given radar image of a scene into the image which would have been recorded by a different radar being flown on a different heading and at a different altitude over the same scene. This can be seen to be of interest in pre-mission briefings and in making navigation aids for guidance.

Some additional applications to which the point scattering radar image simulation model might be applied are: Evaluation of stereo-radar and Interferometry techniques for elevation determination; the effects of platform instabilities and pointing errors on the resultant imagery, evaluation of hardware designs or specifications to determine potential suitability of the resultant radar system to satisfy the reconnaissance or guidance mission for which it is being built. Many other, similar applications can be listed but these are a representative sampling and adequately demonstrate the diversity of potential applications of radar simulation to the mission objectives of the U.S. Army.

7.2.4.2 Receiver Transfer Function

Radar image simulation should be used to evaluate the degradations imposed on radar imagery by the radar receiver and imaging electronics. This information is potentially important to the reconnaissance, guidance, etc., missions. It is hypothesized that the receiver of a particular type of radar system degrades its imagery in a unique fashion with different systems imparting different degradations. These degradations may be highly nonlinear within the dynamic range of a given scene. Understanding the degradations of various radar systems may increase the interpretability and value of their image products.

The receiver systems, including AGC (Automatic Gain Control), of several radars should be modeled and implemented in our simulation computer programs. Simulations of the same radar data base and flight parameters should be formed using one of the receiver models per image. The simulated radar images of the chosen data base should then be evaluated and compared. The interpretability of each simulated image should be assessed and differences from image to image should be identified. These measures should then be correlated with the receiver electronics and spatial variation of the features in the scene (this is easy since the data base represents a known input spatial variation). The results should be made available to image interpreters and radar hardware users and designers for the next generations of designs.

7.2.4.3 Automatic Gain Control (AGC) Effects

It has been observed that AGC produces detectable effects in radar images. These effects span the range from the far-shore brightening to

other, less obvious effects. To increase the accuracy of simulation, AGC effects should be modeled and the model implemented in our radar image simulation computer programs.

Various alternative AGC concepts could be analyzed and their effects on the resultant imagery should be catalogued. Optimal AGC designs might be determined for each specific operational use of radar imagery. The selection being made to maximize detection of a particular feature, or to minimize the perturbations due to a particular feature. This information could then be called upon when selecting a radar system, or designing a radar system for a particular mission. It would also be valuable to the photo-interpreter who is using the imagery obtained for that mission.

7.2.4.4 Synthetic Aperture Radar (SAR) Image Simulation Model

The radar image simulation technology developed in previous work should be extended to medium to high-resolution SAR systems. A study needs to be initiated to develop a SAR simulation model based upon the point scattering approach. The various SAR phenomena such as Doppler processing, constant azimuth resolution, coherent signal processing, etc., are to be modeled as required.

The SAR simulation model should be implemented on the digital computer. A data base should be constructed of a particular site and simulated images should be formed to validate the model.

This recommendation is based upon apparent trends in radar systems development. With the advent of micro-computers and LSI (Large-Scale Integration), digital processing of SAR data is making viable operational uses of high-resolution SAR systems. These operational uses will be found increasingly in both reconnaissance and change-detection missions. Therefore, since radar image simulation is a potentially important advanced tool to support these missions, development of a SAR simulation model is deemed necessary.

ABBREVIATIONS AND ACRONYMS

AGC	Automatic Gain Control
ASF	Area Spatial Filtering Radar Image Simulation Model
CRT	Cathode Ray Tube
DMA	Defense Mapping Agency
DOS	Disk Operating System
ETL	Engineer Topographic Laboratories, U. S. Army, Fort Belvoir, Virginia
FM	Frequency Modulation
IDECS	Image Discrimination, Enhancement, Combination, and Sampling
I/O	Input/Output
IR	Infra-Red (Images)
PDP-15	Mini-Computer Manufactured by the Digital Equipment Corporation, Massachusetts
PIXEL	Picture Element
PPI	Plan-Position Indicator
PSM	Point Scattering Radar Image Simulation Model
RF	Radio Frequency
RSL	Remote Sensing Laboratory, University of Kansas, Lawrence, Kansas
SAR	Synthetic Aperture Radar
σ^0	Differential Scattering Cross-Section (Backscatter Per Unit Area)
SLAR-REAL	Side-Looking Airborne Radar - Real Aperture
SLAR-SAR	Side-Looking Airborne Radar - Synthetic Aperture
USGS	United States Geological Service
UTM	Universal Transverse Mercator (Mapping Projection)

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